AD/A-000 383

EXPERIMENTAL EVALUATION OF A RELIABILITY ASSESSMENT MODEL FOR ADHESIVELY BONDED JOINTS

DAYTON UNIVERSITY

PREPARED FOR
AIR FORCE MATERIALS LABORATORY

JUNE 1974

DISTRIBUTED BY:

NTIS
National Technical Information Service
U. S. DEPARTMENT OF COMMERCE

AD A000383

EXPERIMENTAL EVALUATION OF A RELIABILITY ASSESSMENT MODEL FOR ADHESIVELY BONDED JOINTS

A.P. Berens
P.E. Johnson
B.S. West

University of Dayton Research Institute

TECHNICAL REPORT AFML-TR-74-120

June 1974

PRICES SUBJECT TO CHANGE

Approved for public release; distribution unlimited.

Air Force Materials Laboratory
Air Force Systems Command
Wright-Patterson Air Force Base, Ohio 45433

88

NOTICE

When Government drawings, specifications, or other data are used for any purpose other than in connection with a definitely related Government procurement operation, the United States Government thereby incurs no responsibility nor any obligation whatsoever; and the fact that the government may have formulated, furnished, or in any way supplied the said drawings, specifications, or other data, is not to be regarded by implication or otherwise as in any manner licensing the holder or any other person or corporation, or conveying any rights or permission to manufacture, use, or sell any patented invention that may in any way be related thereto.

Copies of this report should not be returned unless return is required by security considerations, contractual obligations, or notice on a specific document.

AIR FORCE/56780/8 October 1974 — 200

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER AFML-TR-74-120	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER AD/A-000 383
4. TITLE (and Subtitle) EXPERIMENTAL EVALUATION OF A RELIABILITY ASSESSMENT MODEL FOR ADHESIVELY BONDED JOINTS		5. TYPE OF REPORT & PERIOD COVERED Final Report (October 1972 through April 1974)
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Alan P. Berens Paul E. Johnson Blaine S. West		8. CONTRACT OR GRANT NUMBER(s) F33615-72-C-2161 Air Force Contract
9. PERFORMING ORGANIZATION NAME AND ADDRESS University of Dayton Research Institute 300 College Park Avenue Dayton, Ohio 45469		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS Project No. 7340 Task No. 734002
11. CONTROLLING OFFICE NAME AND ADDRESS AFML/MBM Wright-Patterson Air Force Base, Ohio 45433		12. REPORT DATE June 1974
		13. NUMBER OF PAGES 77
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

adhesive joints
fatigue tests
static tests
reliability
accelerated testing
residual strength
shift factors

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Adhesively bonded joints were failed statically and in fatigue to test the validity of a fatigue life assessment model. The results of the tests were in agreement with both the assumptions and the predictions of the model. In particular, the failure mode was constant for all tests and the observed static strength and fatigue lives were adequately modeled by the Weibull family of distributions with constant, but different, shape parameters over the range of test conditions considered. The predicted relationship between the shape

DD FORM 1473, 1 JAN 73 — EDITION OF 1 NOV 65 IS OBSOLETE

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

20. Abstract

parameters as a function of an experimentally determined material property was observed. The predicted distribution of residual strength as a function of time in the fatigue environment was verified and agreement between prediction and observation for an accelerated fatigue test was obtained.

FOREWORD

The work reported herein was performed by the Aerospace Mechanics Division of the University of Dayton Research Institute under Air Force Contract F33615-72-C-2161. The effort was initiated under Project 7340, "Nonmetallic and Composite Structures," Task No. 734002, "Structural Adhesives." The contract was administered by the Non-Metallics Materials Branch, Air Force Materials Laboratory, Wright-Patterson Air Force Base, Ohio. The Air Force Project Engineers directing the program were Messrs. K.L. Jerina, R.J. Dauksys and G.E. Husman of AFML/MBC. The project effort was conducted during the period of October 1972 through April 1974.

The authors sincerely acknowledge the advice and assistance of Dr. J.C. Halpin of the Air Force Materials Laboratory.

This manuscript was released by the authors in May 1974.

This technical report has been reviewed and is approved for publication.

George E. Husman
GEORGE E. HUSMAN
Project Engineer

T.J. Reinhart Jr.
T.J. REINHART
Chief, Composites and
Fibrous Materials Branch

ABSTRACT

Adhesively bonded joints were failed statically and in fatigue to test the validity of a fatigue life assessment model. The results of the tests were in agreement with both the assumptions and the predictions of the model. In particular, the failure mode was constant for all tests and the observed static strength and fatigue lives were adequately modeled by the Weibull family of distributions with constant, but different, shape parameters over the range of test conditions considered. The predicted relationship between the shape parameters as a function of an experimentally determined material property was observed. The predicted distribution of residual strength as a function of time in the fatigue environment was verified and agreement between prediction and observation for an accelerated fatigue test was obtained.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF TABLES

LIST OF TABLES (Continued)

LIST OF TABLES (Continued)

SECTION I

INTRODUCTION

This report presents the results of an experimental program designed to test the applicability of a reliability evaluation model to the structural behavior of adhesively bonded joints. This model, developed by Halpin, Jerina and Johnson, Reference 1, is based on a structural reliability assessment methodology that has evolved as a result of developments in reliability analysis, kinetic fracture mechanics, and the introduction of the closed-loop fatigue testing machines. The essential features of the approach may be summarized as follows. Fatigue failure occurs when the applied stress exceeds the residual strength of the structure. Repeated low-level stresses reduce the residual strength, and it is postulated that the mechanism for this strength reduction is the growth of flaws which are inherent to all structures. Under this hypothesis a model was developed which yields the distribution of strength as a function of time in the testing environment. The model is a function of the statistical parameters of the initial strength distribution and the fatigue life distribution, the slope of the flaw growth rate equation, a material constant, and the maximum applied stress in the fatigue spectrum. Further, by analogy with the methods of viscoelastic analysis, Tsai, Halpin, and Pagano, Reference 2, the statistical parameters of the strength and time-to-failure distributions are modeled by well defined, shift factor type relationships when the tests are performed under varying conditions of stress and temperature environments. The shift factor relationships are derived from static tests and are applied to fatigue tests, thus allowing the fatigue tests to be performed in an accelerating environment.

To validate this model as an engineering tool in the fatigue life assessment of quasi-brittle adhesives, specimens were statically tested at various combinations of temperature and loading rate and fatigue tested at several levels of constant amplitude load at room temperature. The test specimen

used for the experimental program was a double lap joint configuration with graphite/epoxy and titanium adherends and Reliabond 398 as the bonding agent. The resulting data were then analyzed to test basic assumptions and parameter relationships of the model. Using a shift factor derived from the static tests, the predicted life from an accelerated fatigue test was compared to the observed life.

SECTION II

ANALYTICAL FRAMEWORK

The complete derivation of the fatigue life methodology under consideration is presented in [1], but in order to establish notation and to specify the equations of interest in this study, the following summary of the analytical framework is presented. Assume that the strength of a structure is a function of the size of the maximum flaw and that flaw growth can be approximated by

$$\frac{dc}{dt} = M \cdot c^r \qquad , \; r \geq 1 \tag{1}$$

where r is a material constant independent of test or service environment and M is dependent on the test or service environment. Then, if $t_o = 0$, the residual strength at time t under a loading environment is derived as

$$F(t)^{2(r-1)} = F(0)^{2(r-1)} - t(r-1)\,A\,F_{max}^{2r} \tag{2}$$

where

$F(t)$ = strength at time t

A = environment constant

F_{max} = maximum applied stress in fatigue spectrum

This equation implies that strength at time t is a deterministic function of the unknown initial static strength. Assuming that the initial static strengths have a Weibull distribution

$$P[F(0) > F] = \exp - [F/\hat{F}(0)]^{\alpha_o} \tag{3}$$

where α_c is the shape parameter and $\hat{F}(0)$ is the scale parameter (characteristic life), from Equations (2) and (3)

$$P[F(t) > F] = P\left\{ F(0) > \left[F^{2(r-1)} + t(r-1) A F_{max}^{2r} \right]^{\frac{1}{2r-1}} \right\}$$

$$\text{exp} - \left[\frac{F^{2(r-1)} + t(r-1) A F_{max}^{2r}}{\hat{F}(0)^{2(r-1)}} \right]^{\alpha_f} \quad (4)$$

where $\alpha_f = \alpha_o/2(r-1)$. Since fatigue failure occurs when the applied stress exceeds the strength, the probability of survival to time t is $P[F(t) > F_{max}]$. For $F = F_{max} << \hat{F}(0)$, Equation (4) for the fatigue life distribution can be approximated by

$$P[t_f > t] = P[F(t) > F_{max}]$$

$$= \exp - [t/\hat{t}]^{\alpha_f} \quad (5)$$

where

$\hat{t}_f$ = characteristic fatigue life

$$= \frac{\hat{F}(0)^{2(r-1)}}{(r-1) A F_{max}^{2r}} \quad (6)$$

(It should be noted that for this study $\alpha_o \approx 11$, $r \approx 5$ and the maximum ratio of $F_{max}/\hat{F}(0) = 0.615$ which resulted in less thar a 1 percent error in the approximate fatigue life distribution.) By estimating $\hat{t}_f$ from fatigue tests

for a given fatigue stress history, Equation (4) can be used to generate the distribution of residual strengths after the structures have been exposed to the fatigue environment for a time t. Further, from Equation (6)

$$\hat{t}_f F_{max}^{2r} = \frac{\hat{F}(0)^{2(r-1)}}{(r-1)A} = B \tag{7}$$

where B is a material constant for a fixed test environment. Hence, a plot of log F_{max} vs log $\hat{t}_f$ is linear with slope $-1/2r$.

Equation (5) implies that, for a fixed mode of failure, the shape parameter of the time to fatigue failure distribution is independent of history, load, or environmental and side effects. The fatigue life shape parameter is functionally related only to the initial static strength shape parameter, α_o, and the material constant, r. The scale parameter, however, is dependent on the environmental conditions. In particular, for a thermal variation with all other environmental conditions held constant, if

$$M = A_1 \exp - (\Delta H/RT) \tag{8}$$

where ΔH is a classical activation energy, R is the gas constant, and A_1 is a material parameter then

$$A = A_2 \exp - (\Delta H/RT) \tag{9}$$

where A_2 is a material parameter. If a_T is the ratio of the characteristic lifes between temperature T, and a reference temperature, T_o, then

$$a_T = \frac{\hat{t}_f(T_o)}{\hat{t}_f(T)} \tag{10}$$

and substituting A values from Equation (9) in Equation (7) yields

$$\log a_T = \frac{-\Delta H}{2.3\ R}\left(\frac{1}{T} - \frac{1}{T_o}\right) \tag{11}$$

Since the shape of the fatigue life distribution is constant, the effect of a temperature change is to shift the location of the distribution and a_T is called the shift factor.

If static tests are performed by applying a constant loading rate history, $F(t) = Vt$, it is shown that the breaking strengths, F_b, have a Weibull distribution

$$P[F_b > F] = \exp - [F/\hat{F}_b]^{\alpha_o} \tag{12}$$

where

$$\hat{F}_b = [B'(2r+1)V]^{1/2r+1} \tag{13}$$

$$\alpha_o = 2r+1 \tag{14}$$

and B' is dependent on thermal and other environmental effects. Since $\hat{F}_b = V\hat{t}_b$, Equation (13) can be written in the form

$$\hat{t}_b\ \hat{F}_b^{\ 2r} = B'(2r+1) \tag{15}$$

Thus, a plot of $\log \hat{F}_b$ vs $\log \hat{t}_b$ is linear with slope $-1/2r$ and is parallel to the corresponding plot for fatigue lives, Equation (7). To shift the static time to break curve from temperature i to reference temperature R, assume

$a_T = B'_i/B'_R$. Then by taking the ratio of F_{b_i} to F_{b_R} as expressed in Equation (13) yields

$$\log a_T = \alpha_o \log\left[\frac{\hat{F}_{b_i}}{\hat{F}_{b_R}}\right] - \log\left[\frac{V_{ij}}{V_R}\right] \tag{16}$$

where V_{ij} represents loading rate j at temperature i, Halpin [3]. The shift factors can then be applied to the characteristic lives from fatigue tests to permit accelerated testing to locate the fatigue curve on the $\log F_{max}$ vs $\log \hat{t}/a_T$ plot. Since the model indicates the slope of this curve is $-1/2r$, the fatigue curve at usage temperature is thus established.

The objectives of this program can now be specifically stated in terms of the assumptions and predicted relationships of the model. These are:

1. To the extent possible check the applicability of the Weibull model to the static strength and fatigue life distributions.

2. Test the constancy of the Weibull shape parameter for the static strengths and for the fatigue lives.

3. Evaluate the predicted relationships between α_o, α_f and r.

4. Evaluate the predicted distribution of strength as a function of time in the loading environment.

5. Compare the slope of the $\log F_{max}$ vs $\log \hat{t}/a_T$ curves to $-1/2r$.

6. Evaluate the shift factors derived from static tests by performing an accelerated fatigue test and comparing observed results to the predicted.

7. Evaluate the constancy of the failure mode in the adhesively bonded joint.

The results of the studies to meet these objectives are presented in Section IV following the presentation of the test methods.

SECTION III

EXPERIMENTAL PROGRAM

This section of the report briefly describes the experimental procedures used in generating the test data.

3.1 TEST SPECIMEN DESIGN AND FABRICATION

The following paragraphs briefly describe the methods of design and fabrication procedures employed in producing the test specimens.

3.1.1 Test Specimen Configuration

In order to satisfy the program objectives, it was deemed necessary to design a test specimen that would exhibit a cohesive failure in the bonded joint adhesive system. This was accomplished through the use of both analytical and experimental methods.

An initial group of eight test specimens was fabricated per the design shown in Figure 1. Four of these specimens (specimens P-1, P-3, P-5, and P-7) were tested to failure in static tension at a loading rate of 1200 lbs per minute at room temperature and room humidity. The mean failure load was 1,785 lbs for the first joint to fail in each specimen and 1,980 lbs for failure of the second joint. The failure mode was an adhesive failure at the surface of the graphite adherend.

The test specimen configuration was subsequently modified by changing the relationship between the axial stiffness of the adherends. Two additional test specimen configurations were defined and a group of eight specimens was fabricated for each design. The test specimen configurations are shown in Figures 2 and 3. A comparison of the adherend stiffness for all three configurations is presented in Table I. The failure data for all three configurations is summarized in Table II.

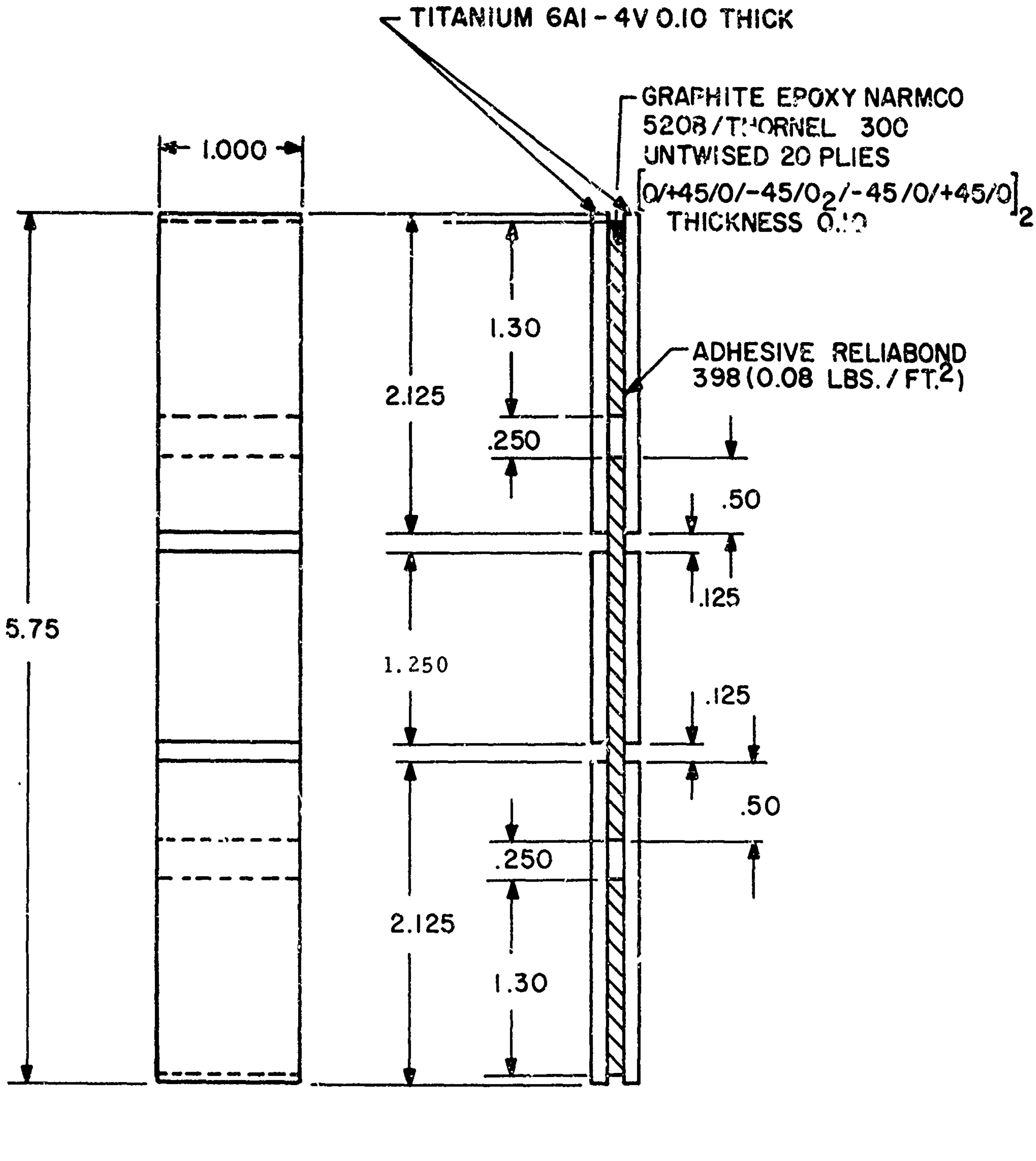

Figure 1. Test Specimen Configuration.

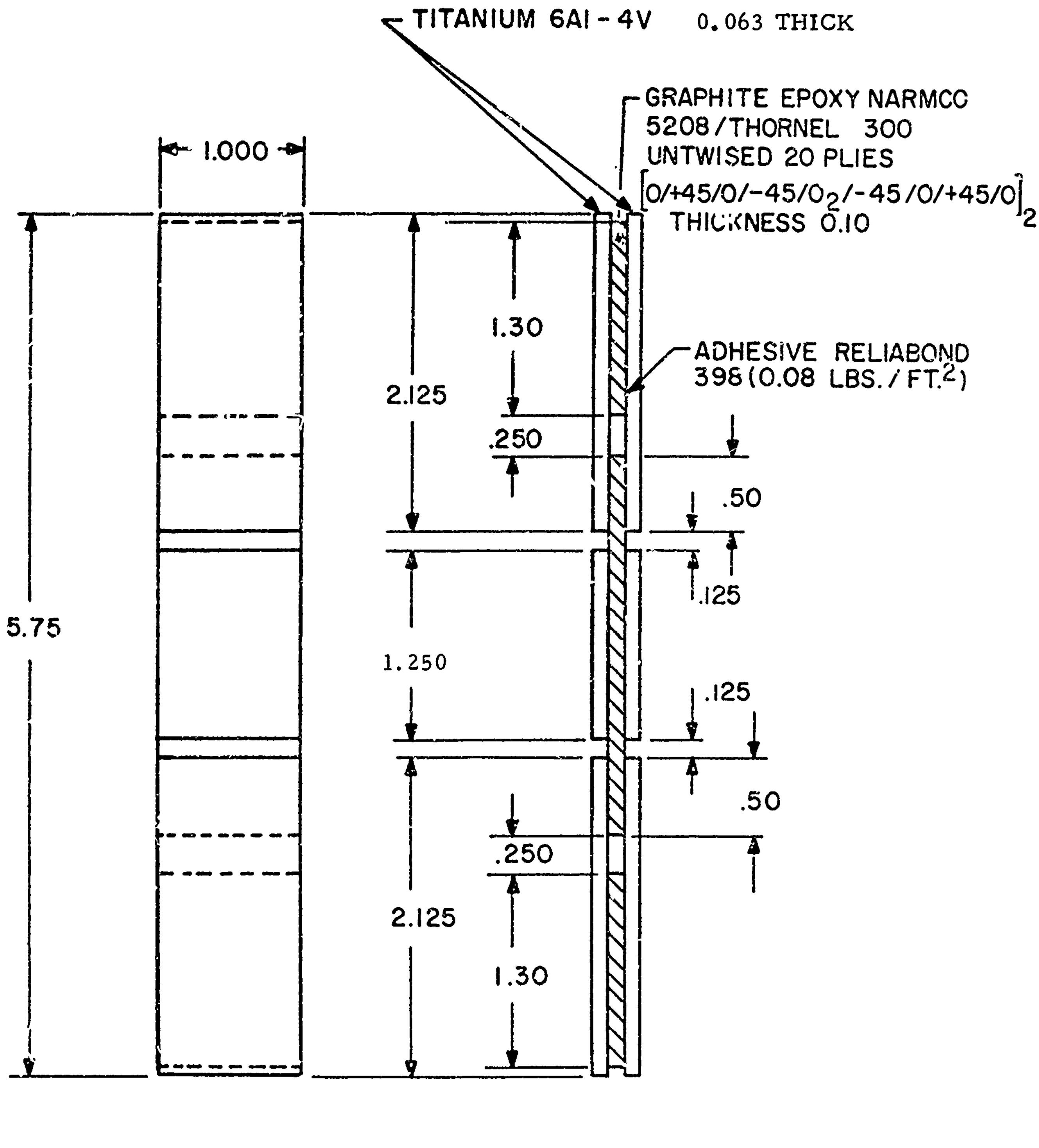

Figure 2. Test Specimen Configuration with Reduced Titanium Adherend Thickness

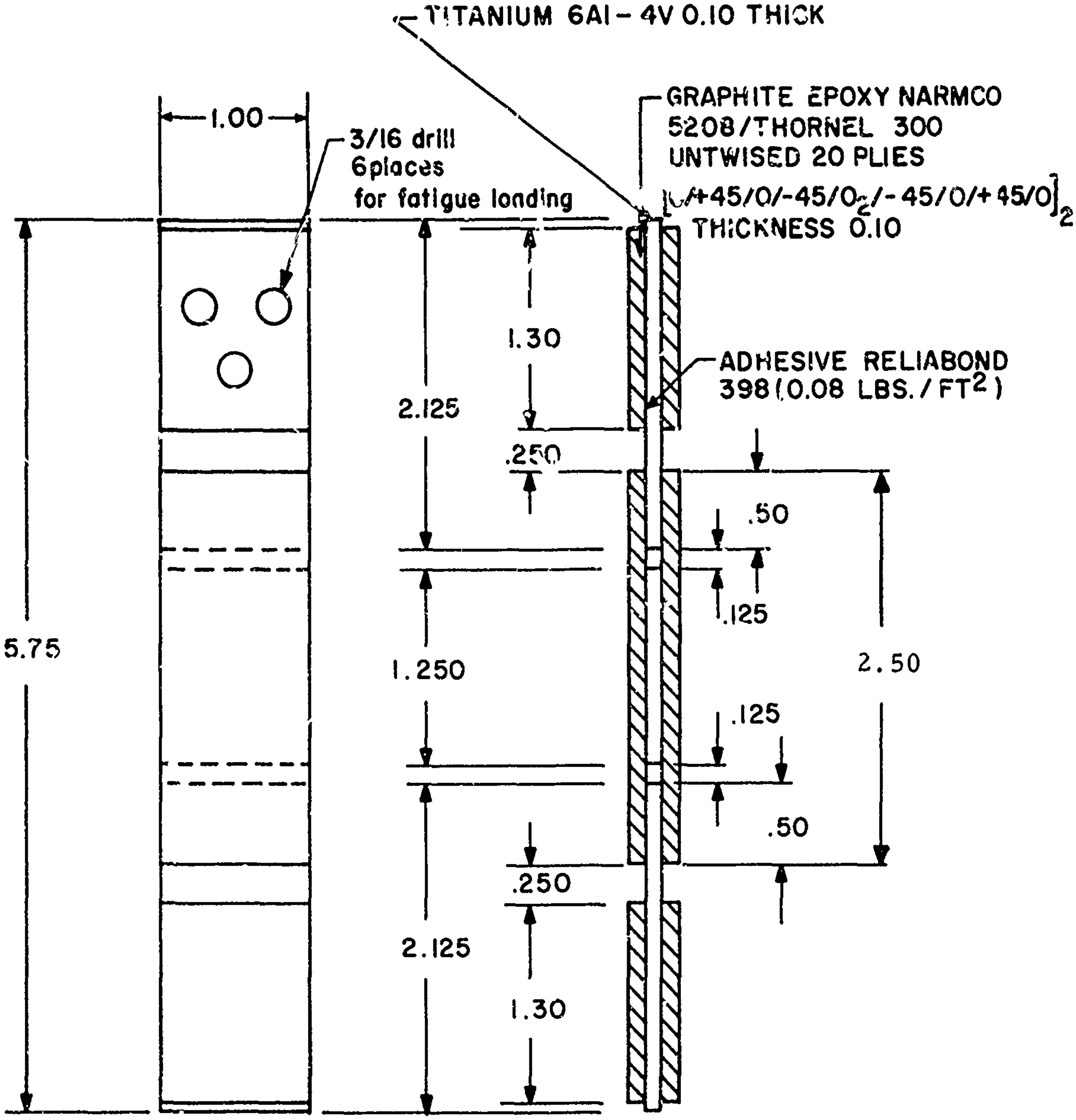

Figure 3. Test Specimen Configuration with Graphite and Titanium Adherend Locations Interchanged.

TABLE I

TEST SPECIMEN ADHEREND STIFFNESS

Specimen Configuration	Σ Et (psi x in) Graphite	Titanium
Figure 1	1.2×10^6	3.4×10^6
Figure 2	1.2×10^6	2.14×10^6
Figure 3	2.4×10^6	1.7×10^6

TABLE II

SUMMARY OF PRELIMINARY TESTING

Specimen No.	Static Tension Failure Load 1st	2nd	Comments
P-1	1750 lbs	1675 lbs	Adhesive failure at graphite adherend-adhesive interface.
P-3	1745	2390	
P-5	1720		
P-7	1920	1875	
Average	1785	1980	
P-9	1700	2000	Adhesive failure at graphite adherend-adhesive interface.
P-11	1770	1700	
P-13	1760	1970	
P-15	1780	2020	
Average	1755	1925	
P-17	4270	3875	Cohesive failure in adhesive system.
P-19	4810	4730	
P-21	4100	4180	
P-23	3520	4520	
Average	4175	4320	

Test specimens P-9, P-11, P-13, and P-15 had the configuration shown in Figure 2. The mean failure load was 1,755 lbs for the first joint to fail in each specimen and 1,925 lbs for failure of the second joint. The failure mode was an adhesive failure at the surface of the graphite adherend.

Test specimen P-17, P-19, P-21, and P-23 had the configuration shown in Figure 3. The mean failure load was 4,175 lbs for the first joint to fail in each specimen and 4,322 lbs for failure of the second joint. The failure mode was a cohesive failure in the Reliabond 398 adhesive system. On the basis of this experimental parametric study, the specimen configuration shown in Figure 3 was selected for use on this experimental research program.

3.1.2 Test Specimen Fabrication

The test specimens were fabricated in panels 5.75 inches long by 9.5 inches wide. From each 5.75 x 9.5 panel a group of 8 test specimens (5.75 x 1) were cut using a diamond impregnated cut-off wheel with liquid cooling. A typical test specimen is shown in Figure 4 and depicted graphically in Figure 3.

Each test specimen was assigned a test specimen identification number prior to layup and cure. The test specimen identification number serves to uniquely identify each specimen. Adherend and test specimen fabrication data were recorded for each test specimen fabricated. Typical data is presented in Figure 5.

3.1.2.1 Graphite/Epoxy Adherend Fabrication

All composite adherends were cut from 38 x 40 inch Narmco 5208/Thornel 300 graphite/epoxy laminate panels purchased from the Whitaker Corporation, Narmco Materials Division, Costa Mesa, California. Cutting of the 1.3 x 9.5 inch tab adherends and the 2.5 x 9.5 inch center

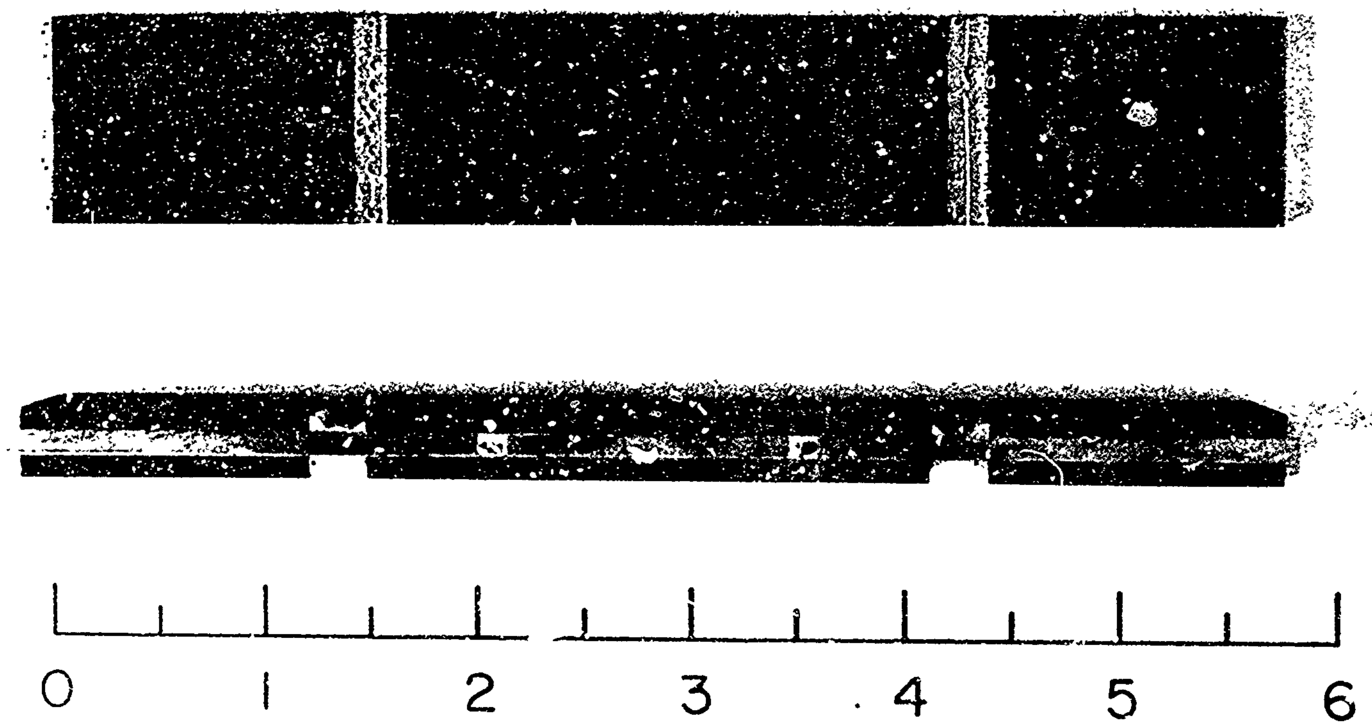

Figure 4. Test Specimen.

SPECIMEN NO.	65	66	67	68	69	70	71	72
GROUP/LOCATION	14-1	14-2	14-3	14-4	14-5	14-6	14-7	14-8
ADHEREND DATA								
Titanium Thickness $t_{a,b}$	0.1010	0.1008	0.1003	0.1004	0.1003	0.1000	0.1012	0.1021
Titanium Thickness $t_{c,d}$	0.1021	0.1022	0.1020	0.1020	0.1016	0.1016	0.1013	0.1012
Graphite Panel Location	GT 14							
Panel No. (front)	26							
Graphite Thickness								
$g_{a,b}$	0.1021	0.1068	0.1094	0.1122	0.1089	0.1102	0.1107	0.1112
$g_{c,d}$	0 1083	0.1072	0.1078	0.1096	0.1090	0.1105	0.1124	0.1111
Panel No. (back)	27							
Graphite Thickness								
$g_{a,b}$	0.1111	0.1089	0.1085	0.1109	0.1121	0.1110	0.1098	0.1073
$g_{c,d}$	0.1080	0.1102	0.1123	0.1112	0.1099	0.1110	0.1110	0.1074
SPECIMEN DATA								
Length	5.733	5.733	5.732	5.733	5.734	5.733	5.733	5.733
Width $W_{a,b}$	1.0031	0.9982	0.9998	0.9930	0.9970	0.9983	0.9987	1.0002
Width $W_{c,d}$	1.0028	0.9990	0.9998	0.9944	0.9962	0.9989	0.9994	0.9998
Thickness T_b	0.3237	0.3231	0.3268	0.3308	0.3280	0.3286	0.3293	0.3302
T_c	0.3280	0.3284	0.3269	0.3304	0.3303	0.3292	0.3308	0.3308
Bond Length L_b	0.4984	0.4992	0.5000	0.4992	0.5009	0.4996	0.4992	0.4992
L_c	0.4961	0.4949	0.4957	0.4949	0.4945	0.4953	0.4953	0.4980
Dbl. Bond Thk. t_b	0.0095	0.0066	0.0086	0.0073	0.0067	0.0074	0.0076	0.0096
t_c	0.0096	0.0088	0.0068	0.0076	0.0098	0.0061	0.0061	0.0111

FABRICATION DATA

Adhesive	Batch	Mold	Lay-up D	Lay-up T	Cure Date	Cure Time	Cure Press	Heat-up Rate	Cure Temp-time
R 398		6	5-25-73	12:00	5-25-73	12:30	30	6°/min	350°/60 min

Figure 5. Typical Graphite Bonded Joint Specimen Information.

adherends was accomplished using a diamond impregnated cut-off wheel with liquid cooling. The graphite/epoxy composite was positioned during the cutting operation to yield adherends with zero degree fibers parallel to the uniaxial loading direction of the test specimen.

3.1.2.2 Titanium Adherend Fabrication

The titanium adherends were machined from 0.10 inch thickness 6Al-4V rolled sheet stock. The machining operation yielded 2.125 x 9.5 inch and 1.25 x 9.5 inch adherends with the rolled direction parallel to the uniaxial loading direction of the test specimens.

3.1.2.3 Specimen Fabrication

Prior to layup and cure the surfaces of the titanium adherends were cleaned with MEK, alkaline cleaned, rinsed, vapor degreased, acid etched, rinsed, dried and primed with Reliabond 398 Type II primer. The surfaces of the graphite/epoxy adherends were prepared for bonding by removing the nylon peel plies.

The 5.75 x 9.5 test specimen panel was formed from the layup of the component parts using the mold design shown in Figure 6. Graphite/epoxy adherends were first placed in the mold followed by a sheet of adhesive (previously cut to size). The titanium adherends were then added followed by another sheet of adhesive and the second set of graphite/epoxy adherends to complete the layup. The dowel pins serve to locate and hold the adherends in the correct location during the cure cycle. Slip fit holes are drilled in the titanium adherends 0.500 inches from the edge to control the length of the bonded joint. The center graphite adherends were cut to fit snugly between the dowel pins.

Three panels were cocured in a Tetrahedron Associates, Inc. 18 x 18 inch Mini-Clave yielding a total of 24 specimens per run. The cure cycle time history was pre-programmed and automatically

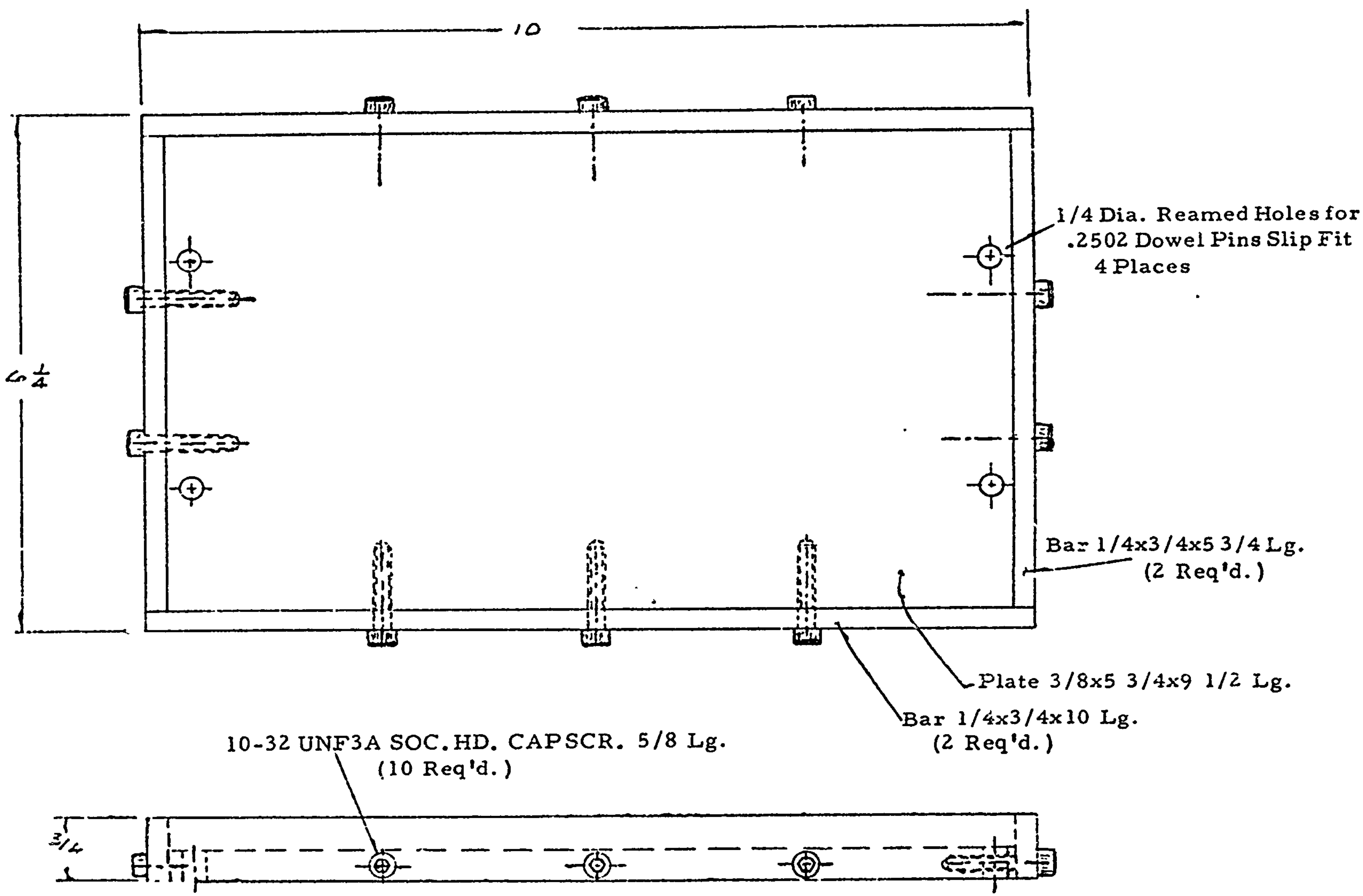

Figure 6. Test Specimen Mold Design.

controlled by closed-loop feedback control from a thermocouple. The control circuit thermocouple and six additional thermocouples were monitored on an x-y plotter for every cure cycle. The cure cycle is depicted graphically in Figure 7. This cycle has a heat-up rate of 6°F/minute and a cure time of 60 minutes at 350°F at a pressure of 30 psig.

Drilling of the fatigue specimens was accomplished using an oversize diamond core drill for drilling the graphite/epoxy adherends followed by a high speed steel twist drill for drilling the titanium adherends.

A total of 440 test specimens were fabricated for this experimental program.

3.1.3 Quality Control of Raw Materials

A total of six 38 x 40 inch Narmco 5208/Thornel 300 graphite/epoxy panels for use as adherends were purchased from the Whitaker Corporation, Narmco Materials Division, Costa Mesa, California. Because of the test specimen redesign described in Paragraph 3.1.1 these laminates were purchased in two lots of three each. The first lot of laminates was ordered on 15 November 1972 and final delivery was made on 12 February 1973. The second lot of laminates was ordered on 21 May 1973 and final delivery was made in late August, 1973.

Some variation in thickness existed for these laminates and it appeared that the location of the joints between the three inch wide preimpregnated tape were not staggered through the thickness of the layup. To insure that this variation would not be reflected in a variable bond-line thickness, the tool plate side of the laminate was used as the joint side of the graphite adherend. Further, for any given test specimen layup, the graphite adherends were taken from adjacent locations in the graphite/epoxy laminate to minimize thickness differences.

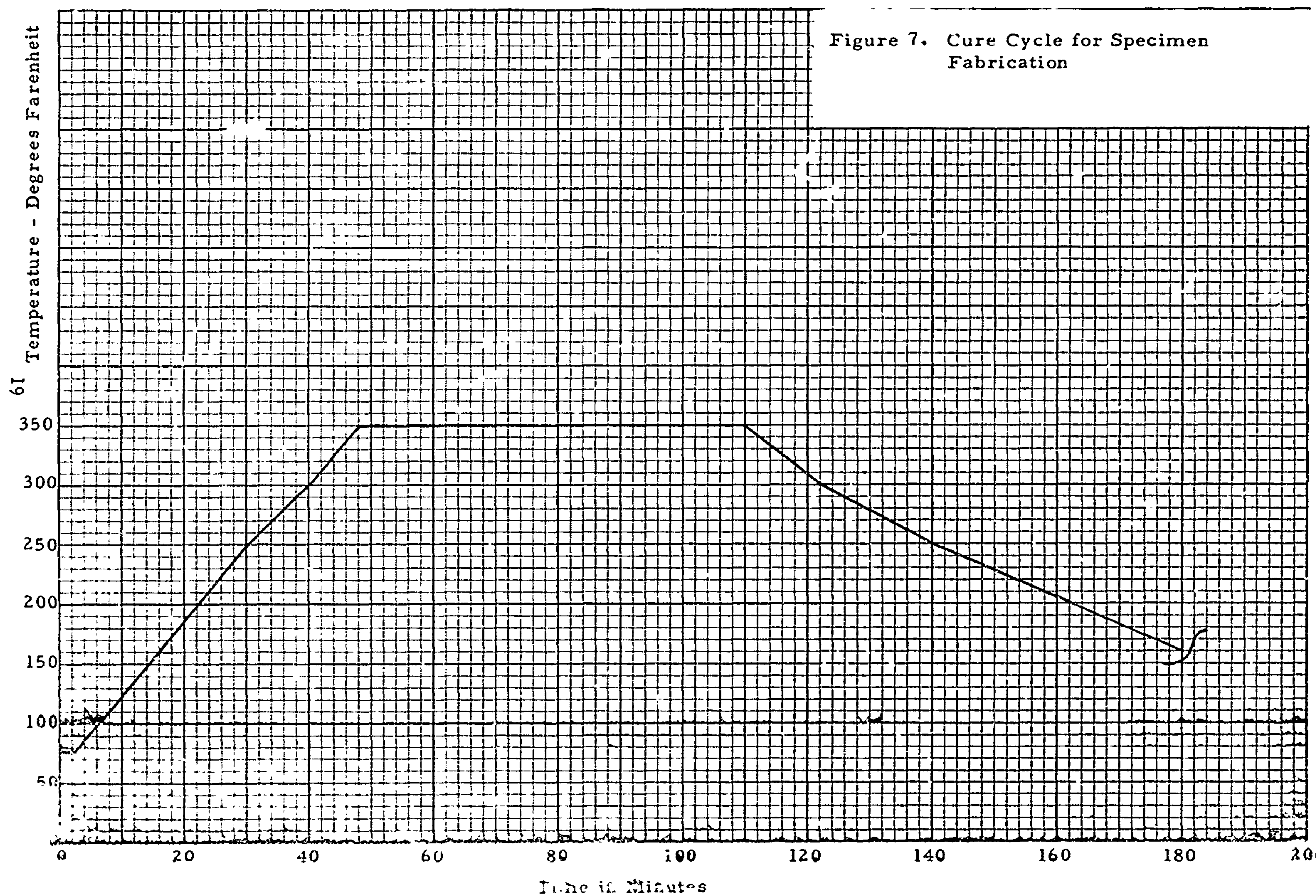

Figure 7. Cure Cycle for Specimen Fabrication

Quality control data for the graphite/epoxy laminates is presented in Tables III through VIII. Two three inch by eight inch 15 ply unidirectional laminates were co-cured with each of the 38 x 40 inch angle ply laminates. One of these was tested by Whitaker Corporation and the other by the University. Longitudinal flexure, transverse flexure, and short beam shear results from these tests are reported in Tables III through VI. In addition, the University has conducted longitudinal and transverse tension tests on specimens taken from each of the $[0/+45/0/-45/0_2/-45/0/+45/0]_2$ angle-ply laminates. Test results for the six laminates are reported in Table VII. The graphite fiber content of the first five graphite/epoxy composite panels was established using optical and acid extraction measurement techniques. Due to the difficulty in establishing the density of the graphite fibers, the fiber volume by the optical method is considered to be the correct value. Fiber volume data for the graphite/epoxy panels is presented in Table VIII.

The titanium sheet stock for the test specimen adherends was received and sized for final fabrication. A significant variation in the titanium sheet thickness from one sheet to the next existed. Therefore, the adherends were sorted and grouped such that all adherends forming any one specimen had the same thickness.

The certified mechanical property test results for the Al-4V titanium material were:

$$\sigma\,\text{ult} = 145,600 \text{ psi}$$

$$\sigma\,\text{yield} = 134,900 \text{ psi}$$

$$\text{Elongation} = 13.5 \text{ percent}$$

The University ordered 150 sq. ft. of Reliabond 398 adhesive from the Reliable Manufacturing Company, Fountain Valley, California. A shipment of 83 sq. ft. of this adhesive was received on 27 December 1972. Since it was desirable that all the adhesive be from one batch, the adhesive

TABLE III

WHITAKER CORP. QUALITY CONTROL TEST RESULTS
FOR NARMCO 5208/THORNEL 300 GRAPHITE EPOXY
15 PLY UNIDIRECTIONAL LAMINATE

Test Result	Panel 1	Panel 2	Panel 3
Longitudinal Flex. Strength	249 ksi	306 ksi	292 ksi
	307	297	305
	313	292	305
Average	305 ksi	299 ksi	300 ksi
University Specification	200 ksi	200 ksi	200 ksi
Transverse Flex. Strength	10 ksi	10 ksi	10 ksi
	12	12	10
	9	9	10
Average	10 ksi	10 ksi	10 ksi
University Specification	9 ksi	9 ksi	9 ksi
Short Beam Shear	17 ksi	18 ksi	17 ksi
	17	16	16
	17	17	16
Average	17 ksi	17 ksi	16 ksi
University Specification	12 ksi	12 ksi	12 ksi
Longitudinal Flex. Modulus	21.3×10^6 psi	21.4×10^6 psi	19.4×10^6 psi
	21.1	20.8	21.0
	23.1	21.4	21.4
Average	21.8×10^6 psi	21.2×10^6 psi	20.6×10^6 psi

NOTE:
1. All tests conducted at room temperature.
2. Longitudinal flexure tests were conducted in 3 point loading at 2.25 inch span.
3. Transverse flexure tests were conducted in 4 point loading at a 2.00 inch span.

TABLE IV

WHITAKER CORP. QUALITY CONTROL TEST RESULTS
FOR NARMCO 5208/THORNEL 300 GRAPHITE EPOXY
15 PLY UNIDIRECTIONAL LAMINATE

Test Result	Panel 4	Panel 5	Panel 6
Longitudinal Flex. Strength	322 ksi	182 ksi	286 ksi
	349	293	302
	360	283	291
Average	343 ksi	253 ksi	293 ksi
University Specification	200 ksi	200 ksi	200 ksi
Transverse Flex. Strength	15.5 ksi	9.3 ksi	9.2 ksi
	10.9	11.0	10.4
	10.1	10.8	11.0
Average	12.2 ksi	10.3 ksi	10.2 ksi
University Specification	9.0 ksi	9.0 ksi	9.0 ksi
Short Beam Shear	17.1 ksi	20.9 ksi	22.0 ksi
	16.3	19.9	26.4
	17.6	22.7	25.4
Average	17.0 ksi	21.2 ksi	24.6 ksi
University Specification	12.0 ksi	12.0 ksi	12.0 ksi
Longitudinal Flex. Modulus	Not Available	Not Available	Not Available
Average			

NOTE:
1. All tests conducted at room temperature.
2. Longitudinal flexure tests were conducted in 3 point loading at 2.25 inch span.
3. Tranverse flexure tests were conducted in 4 point loading at a 2.00 inch span.

TABLE V

UNIVERSITY OF DAYTON QUALITY CONTROL TEST RESULTS FOR NARMCO 5208/THORNEL 300 GRAPHITE EPOXY 15 PLY UNIDIRECTIONAL LAMINATE

Test Result	Panel 1	Panel 2	Panel 3
Londitudinal Flex. Strength	227[a] ksi 259 183	269 ksi 259 289	265 ksi 291 263
Average	221 ksi	272 ksi	273 ksi
University Specification	200 ksi	200 ksi	200 ksi
Transverse Flex. Strength	8.0[a] ksi 8.9 9.5	9.1 ksi 8.9 8.8	7.7 ksi 8.1 8.8
Average	8.8 ksi	8.9 ksi	8.2 ksi
University Specification	9 ksi	9 ksi	9 ksi
Short Beam Shear	13.5[b] ksi 12.6 14.2	10.0 ksi 10.5 10.1	11.0 ksi 12.0 11.0
Average	13.4 ksi	10.2 ksi	11.3 ksi
University Specification	12 ksi	12 ksi	12 ksi
Longitudinal Flex. Modulus	15.8×10^6 psi 16.2 13.9	15.3×10^6 psi 15.3 16.1	16.0×10^6 psi 18.3 17.6
Average	15.3×10^6 psi	15.6×10^6 psi	17.3×10^6 psi

[a]Span to depth ratio of 32:1 tested at cross-head speed of 0.05 in./min.

[b]Span to depth ratio of 5:1 tested at cross-head speed of 0.05 in./min.

TABLE VI

UNIVERSITY OF DAYTON QUALITY CONTROL TEST RESULTS FOR NARMCO 5208/THORNEL 300 GRAPHITE EPOXY 15 PLY UNIDIRECTIONAL LAMINATE

Test Result	Panel 4	Panel 5	Panel 6
Longitudinal Flex. Strength	197[a] ksi	235 ksi	276 ksi
	241	252	241
	228	251	255
Average	222 ksi	246 ksi	257 ksi
University Specification	200 ksi	200 ksi	200 ksi
Transverse Flex. Strength	9.8[a] ksi	9.6 ksi	11.0 ksi
	12.4	10.0	12.3
	8.3	10.3	10.2
Average	10.2 ksi	10.0 ksi	11.2 ksi
University Specification	9 ksi	9 ksi	9 ksi
Short Beam Shear	12.5[b] ksi	11.8 ksi	12.2 ksi
	12.5	12.3	11.1
		11.9	11.1
Average	12.5 ksi	12.0 ksi	11.4 ksi
University Specification	12 ksi	12 ksi	12 ksi
Longitudinal Flex. Modulus	15.9×10^6 psi	15.8×10^6 psi	19.8×10^6 psi
	18.1	21.3	17.3
	16.8	18.8	16.7
Average	16.9×10^6 psi	18.6×10^6 psi	17.9×10^6 psi

[a]Span to depth ratio of 32:1 tested at cross-head speed of 0.05 in./min.

[b]Span to depth ratio of 5:1 tested at cross-head speed of 0.05 in./min.

TABLE VII

UNIVERSITY OF DAYTON QUALITY CONTROL DATA FOR GRAPHITE/EPOXY $[0/+45/0/-45/0_2/-45/0/+45/0]_2$ ANGLE PLY LAMINATE

Specimen	Panel 1 Strength (ksi)	Panel 1 Modulus (ksi)	Panel 2 Strength	Panel 2 Modulus	Panel 3 Strength	Panel 3 Modulus
1LT[a]	133	12.8×10^3	119.5	12.8	123.2	12.7
2LT	137	12.3	113.5	13.6	120.8	12.3
3LT	126	12.5	111.9	13.0	109.8	13.6
Average	132	12.5	115.0	13.1	117.9	12.9
1TT[b]	19.6	1.21	22.6	3.09	22.4	3.17
2TT	20.4	1.45	24.7	2.94	22.7	3.37
3TT	18.2	1.46	22.7	3.15	23.2	3.63
Average	19.4	1.37	23.3	3.06	22.8	3.39

Specimen	Panel 4[c] Strength	Panel 4[c] Modulus	Panel 5 Strength	Panel 5 Modulus	Panel 6 Strength	Panel 6 Modulus
1LT[a]	69.1	13.5	106.0	12.3	Not Available	
2LT	80.0	15.9	84.6	13.1	118.6	13.8
3LT	89.3	14.8	99.6	12.5	111.3	13.3
Average	79.5	14.7	96.7	12.6	114.9	13.5
1TT[b]	19.9	2.77	17.3	1.17	19.4	3.27
2TT	18.5	2.90	17.7	0.55	20.4	2.98
3TT	16.8	3.27	19.1	0.55	18.8	3.45
Average	18.1	2.98	18.0	0.76	19.5	3.23

NOTE:

1. All tests were conducted using standard IITRI test specimens unless otherwise noted.
2. [a] Denotes tests were conducted with the tensile load applied parallel to the zero direction fibers (longitudinal tension).
3. [b] Denotes tests were conducted with the tensile load applied perpendicular to the zero direction fibers (transverse tension).
4. [c] Longitudinal Tension specimens were half scale IITRI specimens for Panel 4.

TABLE VIII

FIBER VOLUME RESULTS FOR GRAPHITE/EPOXY ANGLE PLY LAMINATES

Panel	Density[a] (gram/cc)	Resin Content[b] (% by Weight)	Fiber Volume[c] Acid Extraction	Fiber Volume[c] Optical
1	1.59	29.0	63.9	67.2
2	1.57	28.7	64.4	67.8
3	1.60	28.0	65.1	71.4
4	1.57	29.3	63.6	67.2
5	1.54	31.0	61.5	70.2

[a] Test method ASTM 0792-64T displacement of water.

[b] By acid extraction.

[c] The optical method is considered to be the correct value.

was reordered. A shipment of 156 sq. ft. of Reliabond 398 adhesive from batch 346, supported on cloth and sized to a weight of 0.080 lb per sq. ft. was received on 9 January 1973.

The adhesive quality of the Reliabond 398 adhesive was established at the start and the conclusion of the test specimen fabrication program by fabricating and testing single lap joint shear specimens using 2024-T3 aluminum alloy adherends. These tests were conducted in accordance with ASTM-D1002. The resulting average adhesive strength for seven specimens tested at the start of the fabrication program was 3115 psi and all failures were adhesive. The resulting average adhesive strength for 5 specimens tested at the conclusion of the fabrication program was 3019 psi and again all failures were adhesive. Results of these tests are presented in Table IX and X, respectively.

3.2 TESTING PROGRAM

All static strength and fatigue testing was performed on the University's MTS closed-loop control testing systems.

Specimens tested at nominal room temperature, room humidity conditions were stored at the controlled laboratory conditions of 73±2°F and 60±5 percent relative humidity from completion of fabrication to start of testing.

The specimens tested at high or low temperature at room humidity were subjected to one hour soak times at temperature prior to testing. Both the soak time and testing were conducted in an Instron environmental chamber. Specimens were allocated for testing using a quasi-random selection procedure.

3.2.1 Static Strength Testing

Ten specimens were statically loaded to failure at each combination of five temperatures, T = -40°, 73°, 150°, 250°, and 300°F, and

TABLE IX

QUALITY CONTROL DATA FOR RELIABOND 398 ADHESIVE SINGLE LAP JOINT SHEAR SPECIMENS FABRICATED AND TESTED AT THE START OF THE TEST SPECIMEN FABRICATION PROGRAM

Specimen	Width (in)	Joint Length (in)	Bond Thickness (in)	Ultimate Strength (psi)	Type of Failure
1	.9952	.52	.0050	3,170	Ad
2	.9931	.52	.0054	3,080	Ad
3	.9941	.52	.0045	3,175	Ad
4	.9990	.50	.0057	3,185	Ad
5	.9920	.52	.0045	3,020	Ad
6	1.0019	.50	.0059	2,915	Ad
7	.9931	.50	.0072	3,265	Ad
Average				3,115	

NOTE:
1. Adherends were 2024-T3 aluminum.
2. Cure conditions were 1 hour at 350°F at 30 psig pressure.
3. Heat-up rate was 5-7 degrees per minute.

TABLE X

QUALITY CONTROL DATA FOR RELIABOND 398 ADHESIVE SINGLE LAP JOINT SHEAR SPECIMENS FABRICATED AND TESTED AT THE CONCLUSION OF THE TEST SPECIMEN FABRICATION PROGRAM

Specimen	Width (in)	Joint Length (in)	Bond Thickness (in)	Ultimate Strength (psi)	Type of Failure
1	.9981	.52	.0050	3,025	Ad
2	.9997	.53	.0050	3,133	Ad
3	1.0022	.55	.0057	2,940	Ad
4	1.0040	.55	.0050	2,970	Ad
5	1.0025	.55	.0050	3,029	Ad
Average				3,019	

NOTE:
1. Adherends were 2024-T3 aluminum.
2. Cure conditions were 1 hour at 350°F at 30 psig pressure.
3. Heat up rate was 5-7 degrees per minute.

three loading rates, V = 120, 1200, and 12000 lb/min at room humidity. In addition, the undamaged second joints of the specimens tested at T = 73^{o}F were loaded to failure using the same loading rate and temperature conditions which were used in producing the first joint failure. Ten specimens were also failed at T = 200^{o}F, room humidity, and V = 1200 lb/min. Instron grips with serrated loading wedges were used to transmit the loading to the graphite/epoxy tab adherends for all static strength testing. Load vs time curves were generated and recorded for each static strength test conducted. Static strength test data is presented in Tables XIII through XXVIII in Appendix A.

3.2.2 Fatigue and Residual Strength Testing

Constant amplitude fatigue tests were conducted with R = 0.1 at room temperature (T = 73^{o}F) and humidity for seven levels of maximum load, F_{max} = 3100, 2900, 2700, 2500, 2350, 2150, and 2000 lb. Fifteen specimens were also fatigue tested at T = 200^{o}F and room humidity for F_{max} = 2000 lb. All fatigue specimens were loaded through six 0.1875 inch dia drilled holes as shown in Figure 3. A cumulative count of loading cycles was kept for each fatigue test specimen using digital counters.

Residual strength data was generated by statically testing (at 1200 lb/min, room temperature and humidity) the undamaged second joints of the fatigue specimens tested at F_{max} = 3100, 2900, 2700, 2500, and 2000 lb. Fatigue and residual strength data are presented in Tables XXIX through XXXV in Appendix A. Room temperature fatigue data points are plotted in Figure 8.

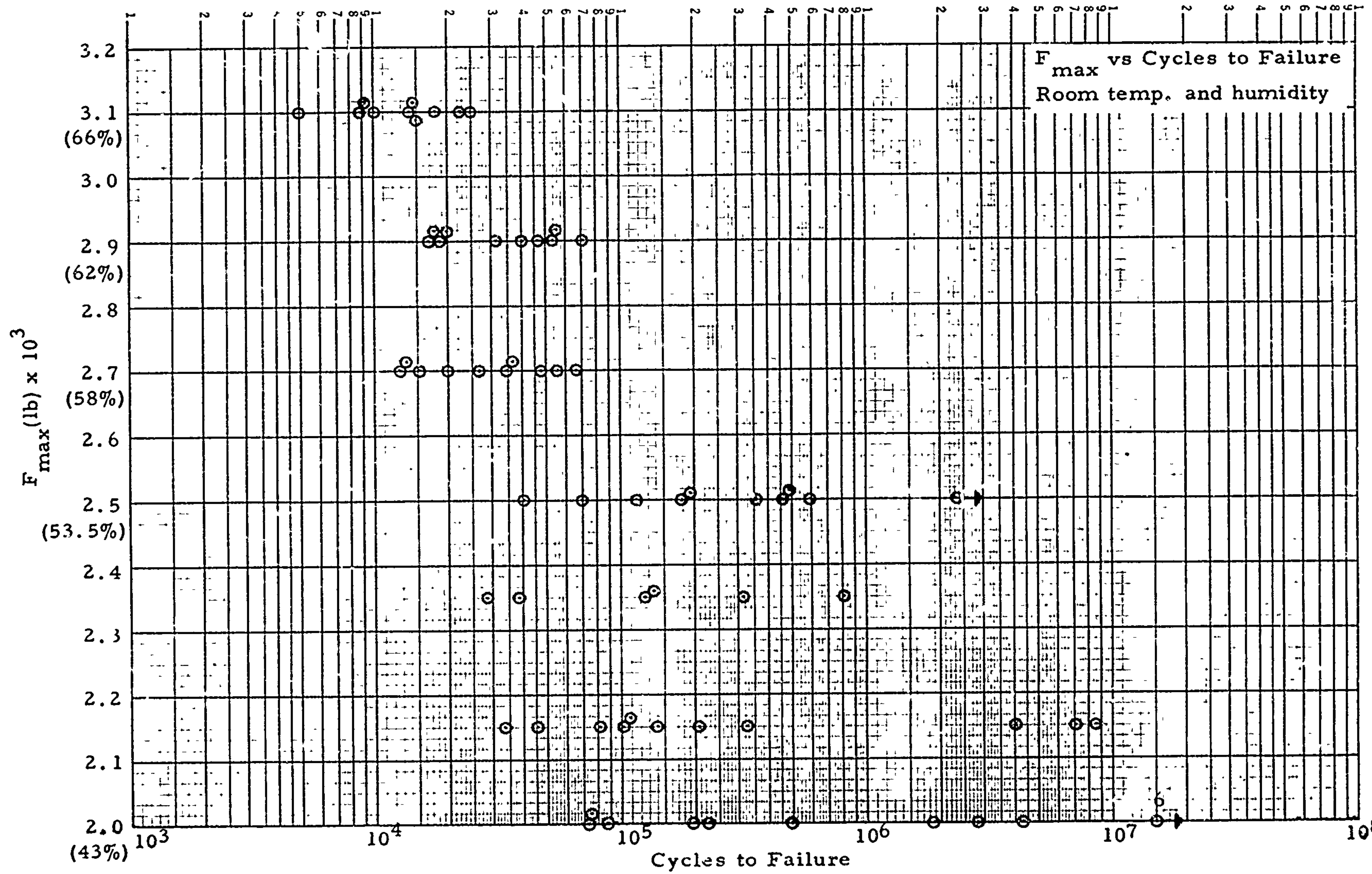

Figure 8. Room Temperature Fatigue Data Points.

SECTION IV

ANALYSIS OF TEST RESULTS

The specific objectives of the test program are enumerated in Section II. To accomplish these objectives, the adhesive joint specimens were tested statically at various combinations of temperature and loading rate and in constant amplitude fatigue at a reference temperature for several levels of maximum applied load and also at an accelerating temperature. The analysis of the resulting data can be considered in three categories: the distributional properties of the static strengths and times to failure; the distribution of residual strength as a function of time in the fatigue environment; and, the determination of the shift factors and their application to the accelerated test result. These categories of analysis are discussed in the following paragraphs.

4.1 DISTRIBUTIONAL PROPERTIES

This category is concerned with the applicability of the Weibull model to the strength and time to fatigue failure distributions, the constancy of the estimates of the Weibull shape parameter, and the predicted relationship between the shape parameter for the static strengths and fatigue lives.

4.1.1 Static Strengths

Ten specimens were statically loaded to failure at each combination of five temperatures, $T = -40^{\circ}$, 73°, 150°, 250°, and $300^{\circ}F$, and three loading rates, $V = 120$, 1200, and 12000 lb/min. Ten specimens were also failed at $T = 200^{\circ}F$ and $V = 1200$ lb/min. The choice of loading rates was arbitrary except that an order of magnitude separation was selected to permit discrimination in the loading rate effect on characteristic strength. The initial choices for test temperature were $T = -40^{\circ}$, 73°, and $300^{\circ}F$. From these tests it was noted that the expected loading rate effect as expressed in Equation (15) was present only at the higher temperatures.

Test were then conducted at the intermediate temperatures to further investigate the effect of loading rate and to obtain several data points for the shift factor vs temperature correlation.

For each of the sixteen sets of static strength data, the maximum likelihood estimates of the scale and shape parameters were obtained. Maximum likelihood estimates were used due to the efficiency of this estimation procedure for small sample size and the ready availability of tables for placing confidence limits on the estimates of the shape and scale parameters, Reference [4]. It should be noted that the maximum likelihood estimate of the shape parameter is biased and that the multiplicative unbiasing factor for a sample of size 10 is 0.859.

Table XI presents the summary statistics including the 90 percent confidence intervals for the shape and scale parameters of the static strength data. Using the criterion of non-overlapping confidence intervals as an indication of a significant difference it can be seen that loading rate for a fixed temperature does not result in significantly different characteristic strengths for temperatures of 150^{o}F and lower, but there is a significant difference for T = 250^{o} and 300^{o}F. For the shape parameters all confidence intervals were overlapping except for the highest, $\alpha_o = 22.06$ at T = 250^{o}F, V = 120 lb/min, with the two lowest $\alpha_o = 8.01$ at T = -40^{o}F, V = 120 lb/min, and $\alpha_o = 8.44$ at T = 73^{o}F, V = 1200 lb/min. Since the highest α_o was the only significantly different value, it is concluded that a value this large was due to chance and that these data indicate a constant shape parameter for static strengths. The failure mode of all of the specimens was determined by examination to be a cohesive failure in the adhesive layer.

4.1.2 Fatigue Lives

Constant amplitude fatigue tests were conducted with R = 0.1 at the reference temperature of T = 73^{o}F for seven levels of maximum load,

TABLE XI

SUMMARY STATISTICS FOR STATIC STRENGTH DATA

$T(^{o}F)$	V(lb/min)	Sample Size	$\hat{F}(0)$(psi)	α_o	90% Confidence limits on $\hat{F}(0)$		90% Confidence limits on α_o	
-40	120	10	5170	8.01	4766	5612	4.43	10.85
	1200	10	5760	11.37	5417	6130	6.00	15.60
	12000	10	5640	13.87	5382	5914	7.68	18.79
73	120	10	5060	12.32	4799	5337	6.82	16.69
	1200	10	4950	8.44	4591	5361	4.67	11.44
	12000	10	5140	13.34	4920	5388	7.97	19.53
150	120	10	4450	11.37	4204	4717	6.29	15.41
	1200	10	4510	8.88	4195	4861	4.91	12.03
	12000	10	4610	13.64	4420	4815	7.89	19.32
200	1200	10	3950	12.98	3758	4157	7.18	17.59
250	120	10	2840	22.06	2758	2927	12.21	29.89
	1200	10	3190	13.68	3046	3352	7.57	18.54
	12000	10	3490	16.01	3349	3634	8.86	21.69
300	120	10	1690	10.95	1596	1799	6.06	14.84
	1200	10	2150	9.08	2001	2311	5.02	12.30
	12000	10	2880	16.51	2769	2997	9.14	22.37

F_{max} = 3100, 2900, 2700, 2500, 2350, 2150, and 2000 lb, and at an accelerating temperature of T = 200°F with F_{max} = 2000 lb. Again all failed specimens were examined for constancy of failure mode and were found to exhibit a cohesive failure in the adhesive layer. In three sets of tests, T = 73°F and F_{max} = 2500, 2150, and 2000 lb, runouts were observed which were an order of magnitude or greater than the characteristic life of the remaining specimens in the set, although no assignable cause could be found for these long lives, they were considered indicative that the distribution of fatigue lives of adhesive joints may be a mixture of distributions with two modes. A second explanation is that the fatigue lives of adhesive joints display extreme variability. A much larger sample size would be required to distinguish between these hypotheses. Since primary interest in the practical problem is in the distribution of the shorter lives, the runouts were eliminated in the following analysis of the fatigue data. In particular, one test was eliminated at P_{max} = 2500 lb, three were eliminated at P_{max} = 2150 lb and the six runouts to 15 x 10^6 cycles at P_{max} = 2000 lb were eliminated (see Figure 8). If the hypothesis of a bimodal distribution is accepted and in view of the relative frequency of early failures (particularly at P_{max} = 2000 lb), perhaps other of the long lives should have been eliminated in the modeling of the earlier failures. In the absence of a definitive criteria for elimination, however, the remaining data points were included in the analysis.

A few comments may be in order concerning the density function of the Weibull distribution. For values of the shape parameter greater than one, the Weibull density function has a single positive mode while for a shape parameter less than one the Weibull density is asymptotic to the vertical axis at the origin. Thus, for shape parameters less than one there is a higher probability of obtaining very early failures than for a shape parameter greater than one. When all fifteen data points at P_{max} = 2000 lb were considered in estimating the shape parameter, using the maximum likelihood equations for a truncated sample, a shape parameter of 0.36 was obtained. This small value

resulted from the scatter introduced from the long lived components. Using the estimate of scale parameter the Weibull distribution indicates a 7 percent probability of a specimen failing before 10,000 cycles. This high of a probability is contrary to experience and is indicative of the lack of fit of the Weibull model to the total data set. Further, by eliminating only the six runouts, a shape parameter of 0.69 was obtained which also yields a reasonably high probability of failure (4.5%) before 10,000 cycles. Therefore, since experience indicates that the Weibull shape parameter should be greater than one, either more high data points should have been assigned to the high modal distribution or the data are not well modeled by the two parameter Weibull distributions. This question cannot be resolved by the data of this study.

The summary of statistics including confidence intervals for the shape and scale parameters of the fatigue test data are presented in Table XII. Again the equality of the shape parameters was tested by the 90 percent confidence intervals but with somewhat inconclusive results. The middle six values were not significantly different but the highest α_f was significantly greater than the three lowest and the lowest value was significantly less than the three highest. Further, there was a distinct decreasing trend in α_f with increasing characteristic life. Nevertheless, in view of the possibility of the lower α_f values being influenced by a bimodality of the fatigue life distribution, it was concluded that the fatigue data does not contradict the assumption of a constant shape parameter for practical engineering applications.

4.1.3 Applicability of Weibull Model

Since each data set in either the static or fatigue tests contains few data points, a test of the Weibull distribution function for each set would not be meaningful. A Kilmogoroff-Smirnov goodness of fit test for a sample of size 10 fails to reject the Weibull hypothesis at a level of significance of 0.2 for all of the data sets but this test has little discriminatory power with a small sample size. However, given a constant shape parameter, dividing

TABLE XII

SUMMARY STATISTICS FOR FATIGUE DATA

$T(^{o}F)$	Max Load (lbs)	Sample Size	$\hat{t}$ (min)	α_f	90% Confidence limits on $\hat{t}$		90% Confidence limits on α_f	
73	3100	10	53	2.62	42	69	1.93	4.73
73	2900	10	140	2.22	104	193	1.23	3.01
73	2700	10	124	1.99	90	174	1.10	2.70
73	2500	9	1020	1.43	627	1679	0.75	1.96
73	2350	6	777	0.92	280	2321	0.38	1.32
73	2150	8	485	1.56	300	802	0.77	2.17
73	2000	9	2870	0.69	1054	8114	0.36	0.95
200	2000	15	367	1.34	253	537	0.86	1.74

each data point by its respective scale parameter yields data sets of 160 points for the static tests and 77 points for the fatigue tests. Further, the transformed data should have a scale parameter of one and shape parameters of α_o and α_f. When this transformation was performed, the unbiased maximum likelihood estimates of the shape parameters were $\alpha_o = 11.23$ and $\alpha_f = 1.26$ with scale parameters of 1.001 and 1.076 for the static and fatigue data, respectively. The unbiased average shape parameters of the individual data sets were $\overline{\alpha}_o = 10.96$ and $\overline{\alpha}_f = 1.37$ which are in agreement with the standardized parameter estimates. The observed cumulative distributions of the transformed data points and their Weibull fits are presented in Figure 9. The differences between the theoretical and observed distributions are not significant and it is concluded that the Weibull distribution is an acceptable model for both the static strength and fatigue life data.

4.1.4 Parameter Relationships

The fatigue characteristic lives are erratic in that a consistent increase in characteristic life was not obtained for decreasing maximum load. No assignable cause could be determined for these results. Nevertheless, a least squares fit was obtained for the log F_{max} vs log $\hat{t}$ (shown in Figure 13) and the slope of this line was -0.101. In accordance with Equation (7), this slope value implies an r value of 5. The value of r obtained from α_o by means of Equation (14) is either 4.98 if the unbiased average α_o is used or is 5.12 if the value of α_o from the standardized static strength is assumed. The differences between these values are not practically significant. Further, $r = 5$ implies by Equation (4) that $\alpha_f = 1.37$ which agrees with the values of α_f calculated from the fatigue test data. Therefore, it is concluded that the data of this study supports the relationships expressed in the model between the shape parameters of the static strength and fatigue life distributions and the flaw growth parameter, r. In all further analyses it was assumed that $r = 5$, $\alpha_o = 11$, and $\alpha_f = 1.37$.

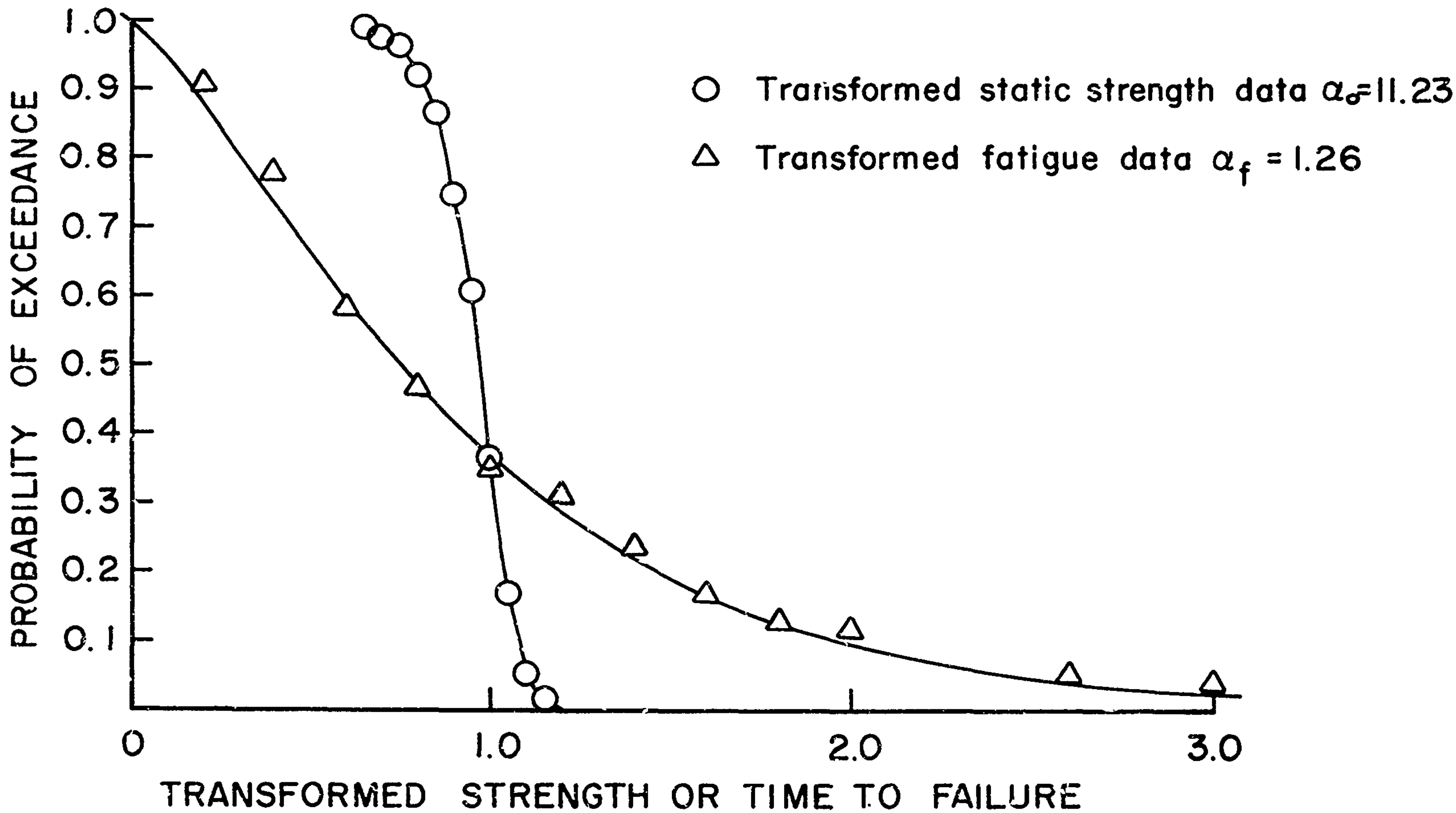

Figure 9. Transformed Static Strength and Time to Fatigue Failure Distribution.

4.2 TIME DEPENDENT RESIDUAL STRENGTH

Equation (4) provides a model for the distribution of strength as a function of time in the fatigue environment. Wolff and Lemon [5] tested the applicability of this aspect of the model by exposing specimens to the fatigue environment for a period of time and statically determining the strength of the unfailed specimens. Since this approach requires additional fatigue specimens and since the present program was directed primarily to the investigation of the shift factor aspects of the model, a different approach to evaluating the time dependent residual strengths was employed. Since each specimen contained two adhesive joints, the strength of the second joint at the time of failure of the first joint was used to provide an indication of the validity of Equation (4).

Since each specimen consists of two joints, the static strength of a specimen can be considered as the minimum of two Weibull random variables which also has a Weibull distribution with a smaller characteristic life and the same shape parameter. In particular, let X denote the random variable of individual joint strength with distribution function given by

$$P(X \geq x) = \exp - [x/\beta]^{\alpha_o} \tag{17}$$

Then if F denotes the strength of a specimen,

$$F = \min (X_1, X_2) \tag{18}$$

and

$$P(F \geq f) = P [\min (X_1, X_2) \geq f]$$

$$= \exp - \left[\frac{f}{\beta 2^{-1/\alpha_o}} \right]^{\alpha_o} \tag{19}$$

Thus, at time zero

$$\hat{F}(0) = 2^{-\frac{1}{\alpha_o}} \beta \qquad (20)$$

where β is the characteristic strength of the individual joints of the specimens.

To determine the characteristic strength, β, of the individual joints and to determine if the application of the load to the failure of the first joint affected the strength of the second joint, the strength of the second (unfailed) joint of the specimens statically tested at T = 73°F were determined. Since no loading rate effect was observed at this temperature, all 60 of the joint strengths were pooled and the maximum likelihood estimate of the characteristic strength of these data was determined to be 5540 psi. Since this value is greater than the predicted (5380 psi) from the minimum of two Weibull random variables as obtained from the specimen tests and Equation (20), it was concluded that loading the stronger joint to the level of first joint failure did not degrade the stronger joint strength and, because of the larger sample size the scale parameter of all joints at T = 73°F was taken as 5540 psi. This is the value used for $\hat{F}(0)$ in Equation (4) since the strength of the stronger joint is being used to test the applicability of the equation. Strictly speaking a higher value should be used since the maximum of the two joints would not be expected to have a characteristic strength equal to the individual joints. However, the maximum of two Weibull random variables is not Weibull and, thus, a characteristic strength determined only from the stronger joint strengths would also not be correct. Therefore, it was decided to use the characteristic strength of all individual joints and subjectively interpret the time dependent residual strengths in view of this compromise.

According to Equation (6), the quantity $\hat{F}(0)^{2(r-1)}/(r-1) A F_{max}^{2r}$ of Equation (4) can be estimated by $\hat{t}_f$ obtained from the fatigue experiment. To estimate $\hat{t}_f$, for a larger static strength characteristic life (second joint

strength) and the same fatigue environment, the ratio of the characteristic lifetimes yields

$$\hat{t}_{f_1} = \hat{t}_{f_R} \left[\frac{\hat{F}_1(0)}{\hat{F}_R(0)} \right]^{2(r-1)} \tag{21}$$

where $\hat{t}_{f_R}$ and $\hat{F}_R(0)$ are the scale parameters of the fatigue lives and static strengths for reference conditions and $\hat{F}_1(0)$ is the increased scale parameter of the initial static strengths of the stronger joint of a specimen.

The undamaged second joints of the fatigue tests run at $T = 73^{\circ}F$ and F_{max} = 3100, 2900, 2700, 2500, and 2000 lb were statically tested to failure. Using Equations (21) and (4), predicted 10th, 50th, and 90th percentiles of the strength distributions for these values of F_{max} were determined as a function of time. The predicted strength percentiles, being a function of the characteristic lives under five values of F_{max}, were widely separated in time. However, transforming the time scale by the predicted median life at each F_{max} level within a data set permitted the five sets of data to be presented on a single plot with less than a 2 percent error in the transformed time scale. Figure 10 presents the predicted percentiles of the strength distribution as a function of trans. rmed time and the observed static strengths of the 42 undamaged joints. The observed strengths are reasonably scattered with respect to the predicted percentile with 25 points above the median and 17 below. Since these joints were actually the stronger of two with the assumed characteristic life, it was expected to have more points above the median line. Further, since the failure times at which these strengths are plotted were determined from the weaker of two joints, the high density of data points at the shorter time was also expected. The results presented on this figure are taken as supportive evidence that the model for predicting strength as a function of time in fatigue environment is applicable to the adhesive joints of this study.

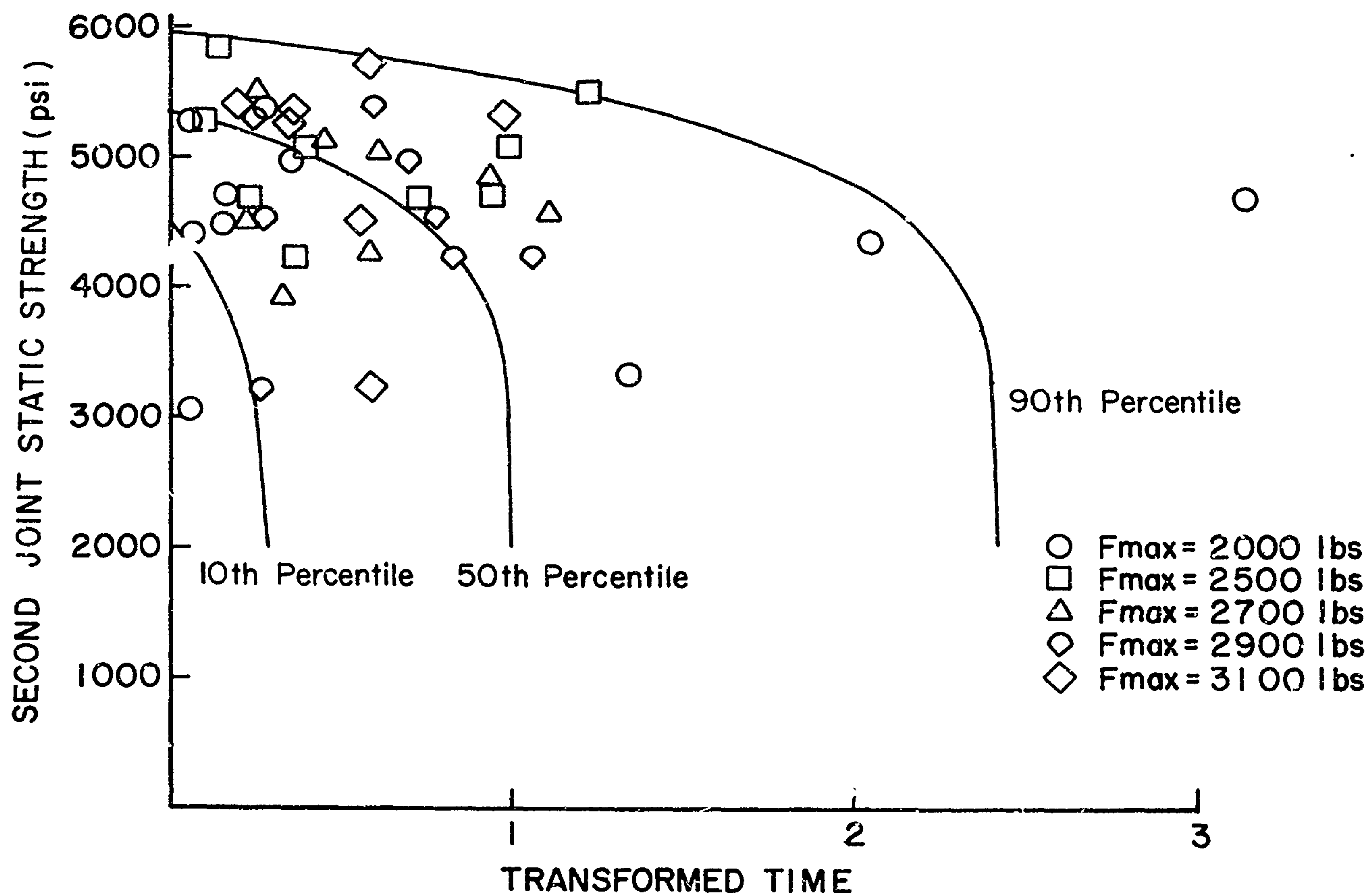

Figure 10. Static Strength as a Function of Transformed Time.

4.3 SHIFT FACTORS FOR ACCELERATED TESTING

The objective in the determination of the shift factors from the static tests is to determine the amount of translation of log $\hat{t}_b$ required to account for the change in strength due to temperature and loading rate. Equation (16) provides an analytical approach to the determination of this shift factor and was applied to the static data with reference conditions taken as $T_R = 73^{\circ}F$ and $V_R = 120$ lb/min. The individual logarithms of the shift factors for each temperature and loading rate and a curve through their average value is shown in Figure 11. The separation of the individual log a_T values at a fixed temperature is due to the difference between the actual and assumed slopes of the log $\hat{F}_b$ vs log $\hat{t}_b$ curves. That is, the order of magnitude separation in the a_T values at $T = 73^{\circ}F$ is due to the lack of effect of loading rate on characteristic strength at this temperature and the log (V_{Rj}/V_R) term of Equation (16) is 0, 1, or 2 depending on the loading rate. Note that selecting $V_R = 1200$ or 12000 lb/min simply increases the log a_T value by 1 or 2, respectively, and does not change the shape of the log a_T vs T curve. It is apparent from this figure that the a_T values for the three loading rates would be equal at about $T = 275^{\circ}F$. Thus, in this temperature range the log $\hat{F}_b$ vs log $\hat{t}_b$ curve would have the assumed slope of $-1/2r$. Using the average log a_T values for each temperature, the resultant log $\hat{F}$ vs log $\hat{t}/a_T$ relationship is presented in Figure 12. The decrease of characteristic strength with temperature and the linear relationship of log $\hat{F}_b$ vs log $\hat{t}_b$ for fixed temperature are apparent in the figure.

To test the applicability of the derived shift factors to fatigue lives, fifteen specimens were tested in constant amplitude fatigue at a temperature of $200^{\circ}F$ with $F_{max} = 2000$ lb and $R = 0.1$. The shifted fatigue life from this test was compared to the results of the fatigue tests performed at the reference temperature of $73^{\circ}F$. This comparison is presented in Figure 13 which is a plot of log F_{max} vs log $\hat{t}/a_T$ where log $a_T = -1.00$ for $T = 73^{\circ}F$ and log $a_T = -2.18$ for $T = 200^{\circ}F$. The straight line shown on this graph is

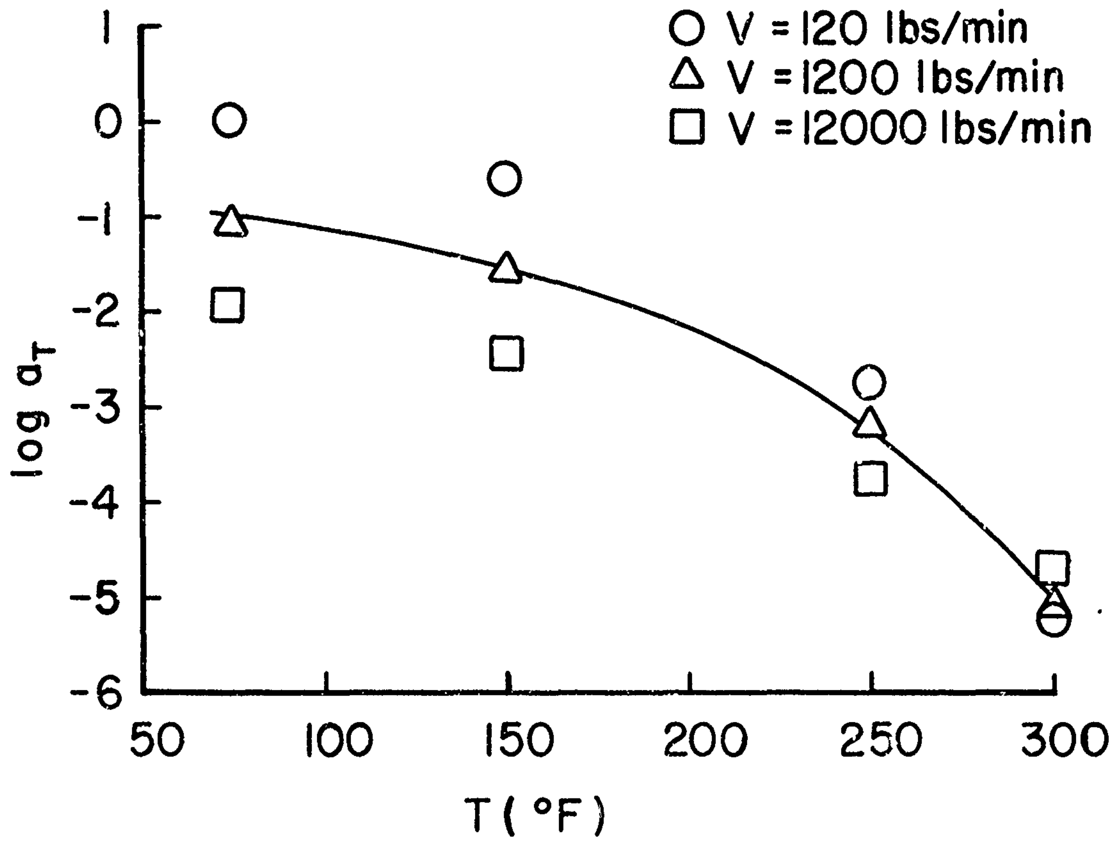

Figure 11. Shift Factors as a Function of Temperature.

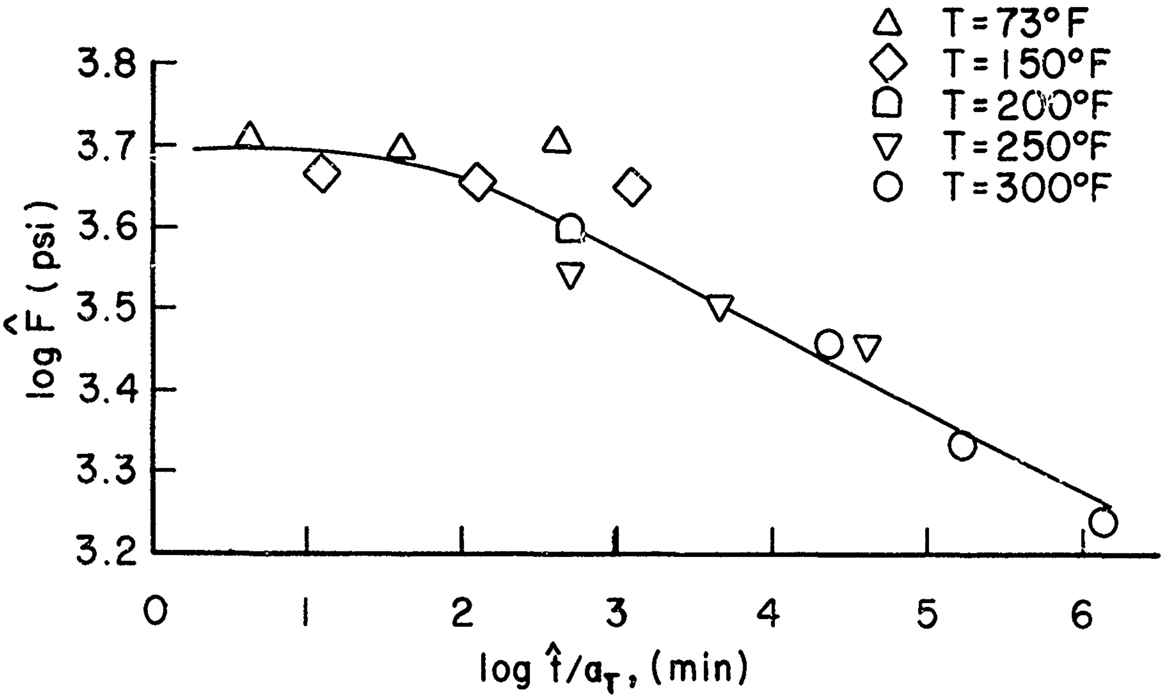

Figure 12. Characteristic Life as a Function of Transformed Time to Break.

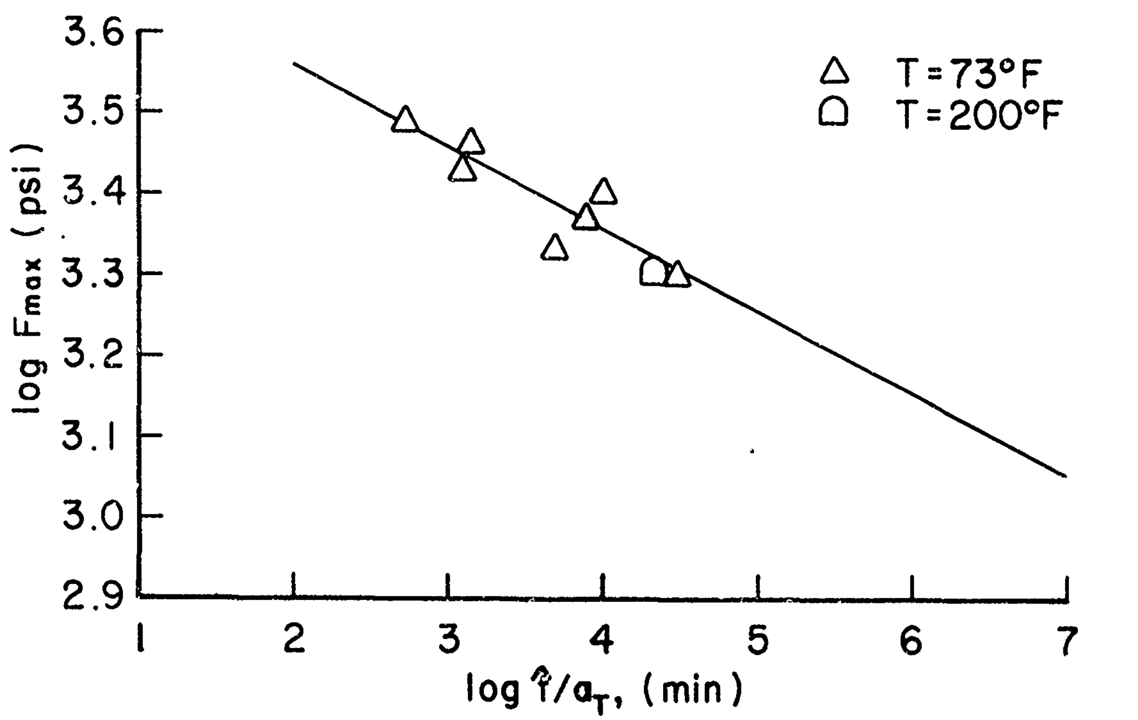

Figure 13. Maximum Load as a Function of Transformed Life.

the least squares line through the reference temperature data and the slope of this line -0.101 agrees with the predicted slope of $-1/2r = -0.10$. As can be seen from Figure 13, the shifted $\hat{t}$ value for the accelerated test agrees well with the predicted value. Therefore, the analytical framework of the model yielded an acceptable agreement between theory and data for this one accelerated test.

SECTION V

CONCLUSIONS

The objective of this study was to experimentally verify a fatigue life assessment methodology for a brittle adhesively bonded joint. The particular aspects of the model that could be verified in the study and the conclusions drawn are as follows:

1) The static strengths were adequately described by the Weibull distribution with a constant shape parameter over the range of test temperatures and loading rates considered.

2) If long life outliers are eliminated from the analysis, the fatigue lives are adequately described by the Weibull distribution with a constant shape parameter. No assignable cause could be found for the outliers but their inclusion lead to parameter estimates which are not in agreement with experience.

3) The model relationships between the shape parameters of the static strengths and fatigue lives and the flaw growth rate parameter were verified.

4) The predicted distribution of strength as a function of time in the fatigue environment agreed with the observed strengths of the second joint of a specimen at the time of first joint failure.

5) On the basis of one test, agreement was observed between prediction and observation of an accelerated fatigue test.

6) The failure mode of all tests was a cohesive failure in the adhesive.

APPENDIX A

TEST DATA

TABLE XIII

STATIC STRENGTH, T = -40^{o}F, V = 120 LB/MIN

TEST TYPE										
First Joint	Low Temperature Static Tensile Strength									
Second Joint										
FIRST JOINT	Temperature		Loading Rate or Frequency			Max. Fatigue Load Level			Fatigue Load Ratio (R)	
TESTING PARAMETERS	-40^{o}F		120 lb/min							
SECOND JOINT	Temperature		Loading Rate or Frequency							
TESTING PARAMETERS										
Specimen Number	166	175	178	185	190	194	204	216	220	227
FIRST JOINT TEST RESULTS										
Failure Strength (psi)	5350	3600	4500	4420	4650	4410	4930	5810	5970	5060
Cycles to Failure										
Joint of Failure	b	c	b	c	b	b	b	c	c	c
SECOND JOINT TEST RESULTS										
Failure Strength (psi)										
STATISTICAL DATA	Number of Data Points		Mean		Standard Deviation		Weibull Scale Parameter		Weibull Shape Parameter	
First Test Joint	10		4870 psi		710 psi		5170 psi		8.01	
Second Test Joint										
ADDITIONAL TEST INFORMATION	Failure strength was determined by dividing the failure load by the shear area of the joint of failure.									
	Each test specimen was soaked 60 min. @ -40^{o}F prior to testing.									

TABLE XIV

STATIC STRENGTH, T = $-40^{\circ}F$, V = 1200 LB/MIN

TEST TYPE										
First Joint	Low Temperature Static Tensile Strength									
Second Joint										
FIRST JOINT	Temperature	Loading Rate or Frequency		Max. Fatigue Load Level			Fatigue Load Ratio (R)			
TESTING PARAMETERS	$-40^{\circ}F$	1200 lb/min								
SECOND JOINT	Temperature	Loading Rate or Frequency								
TESTING PARAMETERS										
Specimen Number	161	170	183	191	196	205	209	212	215	222
FIRST JOINT TEST RESULTS										
Failure Strength (psi)	5060	5780	3900	4870	6010	6250	5890	5930	5200	5910
Cycles to Failure										
Joint of Failure	c	c	c	b	c	b	c	c	c	c
SECOND JOINT TEST RESULTS										
Failure Strength (psi)										
STATISTICAL DATA	Number of Data Points	Mean		Standard Deviation		Weibull Scale Parameter		Weibull Shape Parameter		
First Test Joint	10	5480 psi		720 psi		5760 psi		11.37		
Second Test Joint										
ADDITIONAL TEST INFORMATION	Failure strength was determined by dividing the failure load by the shear area of the joint of failure.									
	Each test specimen was soaked 60 min. @ $-40^{\circ}F$ prior to testing.									

TABLE XV

STATIC STRENGTH, T = -40°F, V = 12000 LB/MIN

TEST TYPE										
First Joint	Low Temperature Static Tensile Strength									
Second Joint										
FIRST JOINT	Temperature	Loading Rate or Frequency		Max. Fatigue Load Level			Fatigue Load Ratio (R)			
TESTING PARAMETERS	-40°F	12000 lb/min								
SECOND JOINT	Temperature	Loading Rate or Frequency								
TESTING PARAMETERS										
Specimen Number	162	164	167	180	188	189	206	211	214	231
FIRST JOINT TEST RESULTS										
Failure Strength (psi)	5090	5380	5690	4060	5400	5640	6070	5580	5250	6020
Cycles to Failure										
Joint of Failure	c	c	c	c	c	c	c	c	c	b
SECOND JOINT TEST RESULTS										
Failure Strength (psi)										

STATISTICAL DATA	Number of Data Points	Mean	Standard Deviation	Weibull Scale Parameter	Weibull Shape Parameter
First Test Joint	10	5420 psi	570 psi	5640 psi	13.87
Second Test Joint					

ADDITIONAL TEST INFORMATION	Failure strength was determined by dividing the failure load by the shear area of the joint of failure.
	Each test specimen was soaked 60 min. @ -40°F prior to testing.

TABLE XVI

STATIC STRENGTH, T = 73°F, V = 120 LB/MIN

TEST TYPE										
First Joint	Static Tensile Strength									
Second Joint	Static Tensile Strength									
FIRST JOINT	Temperature		Loading Rate or Frequency			Max. Fatigue Load Level		Fatigue Load Ratio (R)		
TESTING PARAMETERS	73°F		120 lb/min							
SECOND JOINT	Temperature		Loading Rate or Frequency							
TESTING PARAMETERS	73°F		120 lb/min							
Specimen Number	1	3	5	7	9	11	15	18	21	24
FIRST JOINT TEST RESULTS										
Failure Strength (psi)	4560	5560	4610	4640	5010	4730	5530	5070	4590	4370
Cycles to Failure										
Joint of Failure	c	c	b	c	c	b	b	c	b	b
SECOND JOINT TEST RESULTS										
Failure Strength (psi)	5730	5910	5170	5340	5950	5770	5740	5970	5520	5350

STATISTICAL DATA	Number of Data Points	Mean	Standard Deviation	Weibull Scale Parameter	Weibull Shape Parameter
First Test Joint	10	4870 psi	410 psi	5060 psi	12.32
Second Test Joint	10	5650 psi	280 psi	5770 psi	26.38

ADDITIONAL TEST INFORMATION: Failure strength was determined by dividing the failure load by the shear area of the joint of failure.

TABLE XVII

STATIC STRENGTH, T = 73°F, V = 1200 LB/MIN

TEST TYPE	
First Joint	Static Tensile Strength
Second Joint	Static Tensile Strength

	Temperature	Loading Rate or Frequency	Max. Fatigue Load Level	Fatigue Load Ratio (R)
FIRST JOINT TESTING PARAMETERS	73°F	1200 lb/min		
SECOND JOINT TESTING PARAMETERS	73°F	1200 lb/min		

Specimen Number	25	27	29	31	33	35	39	42	45	48
FIRST JOINT TEST RESULTS										
Failure Strength (psi)	5610	4130	3830	5260	4090	4180	5180	5460	4760	4270
Cycles to Failure										
Joint of Failure	b	c	c	b	c	b	b	c	c	b
SECOND JOINT TEST RESULTS										
Failure Strength (psi)	6000	-	5440	6030	5090	5490	6640	5760	5560	5490

STATISTICAL DATA	Number of Data Points	Mean	Standard Deviation	Weibull Scale Parameter	Weibull Shape Parameter
First Test Joint	10	4680 psi	650 psi	4950 psi	8.44
Second Test Joint	9	5720 psi	450 psi	5930 psi	12.79

ADDITIONAL TEST INFORMATION	Failure strength was determined by dividing the failure load by the shear area of the joint of failure.

TABLE XVIII

STATIC STRENGTH, T = 73°F, V = 12000 LB/MIN

TEST TYPE	
First Joint	Static Tensile Strength
Second Joint	Static Tensile Strength

FIRST JOINT	Temperature	Loading Rate or Frequency	Max. Fatigue Load Level	Fatigue Load Ratio (R)
TESTING PARAMETERS	73°F	12000 lb/min		
SECOND JOINT	Temperature	Loading Rate or Frequency		
TESTING PARAMETERS	73°F	12000 lb/min		

Specimen Number	26	28	30	34	36	38	40	41	44	46
FIRST JOINT TEST RESULTS										
Failure Strength (psi)	4900	4460	5090	5350	5120	4730	5570	4680	5410	4300
Cycles to Failure										
Joint of Failure	c	c	c	c	b	b	b	b	c	b
SECOND JOINT TEST RESULTS										
Failure Strength (psi)	5540	5680	5370	6150	5810	5480	6440	5710	5940	5960

STATISTICAL DATA	Number of Data Points	Mean	Standard Deviation	Weibull Scale Parameter	Weibull Shape Parameter
First Test Joint	10	4960 psi	420 psi	5140 psi	14.34
Second Test Joint	10	5810 psi	330 psi	5960 psi	18.47

ADDITIONAL TEST INFORMATION	
	Failure strength was determined by dividing the failure load by the shear area of the joint of failure.

TABLE XIX

STATIC STRENGTH, T = 150°F, V = 120 LB/MIN

TEST TYPE										
First Joint	High Temperature Static Tensile Strength									
Second Joint										
FIRST JOINT	Temperature		Loading Rate or Frequency			Max. Fatigue Load Level			Fatigue Load Ratio (R)	
TESTING PARAMETERS	150°F		120 lb/min							
SECOND JOINT	Temperature		Loading Rate or Frequency							
TESTING PARAMETERS										
Specimen Number	163	169	181	192	199	202	213	221	225	229
FIRST JOINT TEST RESULTS										
Failure Strength (psi)	38[illegible]	3590	3380	3980	4340	4620	4580	4820	4750	4490
Cycles to Failure										
Joint of Failure	b	c	c	b	b	c	c	b	c	b
SECOND JOINT TEST RESULTS										
Failure Strength (psi)										
STATISTICAL DATA	Number of Data Points		Mean		Standard Deviation		Weibull Scale Parameter		Weibull Shape Parameter	
First Test Joint	10		4240 psi		510 psi		4450 psi		11.37	
Second Test Joint										
ADDITIONAL TEST INFORMATION	Failure strength was determined by dividing the failure load by the shear area of the joint of failure.									
	Each test specimen was soaked 60 min. @ 150°F prior to testing.									

TABLE XX

STATIC STRENGTH, T = 150^{o}F, V = 1200 LB/MIN

TEST TYPE										
First Joint	High Temperature Static Tensile Strength									
Second Joint										
FIRST JOINT	Temperature		Loading Rate or Frequency			Max. Fatigue Load Level			Fatigue Load Ratio (R)	
TESTING PARAMETERS	150^{o}F		1200 lb/min							
SECOND JOINT	Temperature		Loading Rate or Frequency							
TESTING PARAMETERS										
Specimen Number	238	241	246	251	256	262	266	270	277	280
FIRST JOINT TEST RESULTS										
Failure Strength (psi)	4470	4720	4990	3990	4330	4800	3960	4860	3420	2980
Cycles to Failure										
Joint of Failure	b	b	b	c	b	c	c	c	b	b
SECOND JOINT TEST RESULTS										
Failure Strength (psi)										
STATISTICAL DATA	Number of Data Points		Mean		Standard Deviation		Weibull Scale Parameter		Weibull Shape Parameter	
First Test Joint	10		4250 psi		660 psi		4510 psi		8.88	
Second Test Joint										
ADDITIONAL TEST INFORMATION	Failure strength was determined by dividing the failure load by the shear area of the joint of failure.									
	Each test specimen was soaked 60 min. @ 150^{o}F prior to testing.									

TABLE XXI

STATIC STRENGTH, T = 150^{o}F, V = 12000 LB/MIN

TEST TYPE										
First Joint	High Temperature Static Tensile Strength									
Second Joint										
FIRST JOINT	Temperature		Loading Rate or Frequency			Max. Fatigue Load Level			Fatigue Load Ratio (R)	
TESTING PARAMETERS	150^{o}F		12000 lb/min							
SECOND JOINT	Temperature		Loading Rate or Frequency							
TESTING PARAMETERS										
Specimen Number	235	242	248	249	254	258	264	267	269	272
FIRST JOINT TEST RESULTS										
Failure Strength (psi)	4610	4460	4930	3520	4290	4260	4980	4090	4470	4720
Cycles to Failure										
Joint of Failure	c	b	c	c	c	b	b	c	c	c
SECOND JOINT TEST RESULTS										
Failure Strength (psi)										
STATISTICAL DATA	Number of Data Points		Mean		Standard Deviation		Weibull Scale Parameter		Weibull Shape Parameter	
First Test Joint	10		4430 psi		430 psi		4610 psi		13.64	
Second Test Joint										
ADDITIONAL TEST INFORMATION	Failure strength was determined by dividing the failure load by the snear area of the joint of failure.									
	Each test specimen was soaked 60 min. @ 150^{o}F prior to testing.									

TABLE XXII

STATIC STRENGTH, T = 200°F, V = 1200 LB/MIN

TEST TYPE										
First Joint	High Temperature Static Tensile Strength									
Second Joint										
FIRST JOINT	Temperature		Loading Rate or Frequency			Max. Fatigue Load Level			Fatigue Load Ratio (R)	
TESTING PARAMETERS	200°F		1200 lb/min							
SECOND JOINT	Temperature		Loading Rate or Frequency							
TESTING PARAMETERS										
Specimen Number	284	290	302	304	305	318	326	332	343	347
FIRST JOINT TEST RESULTS										
Failure Strength (psi)	3370	3810	3500	3940	4440	3890	3520	3930	3850	3870
Cycles to Failure										
Joint of Failure	c	b	b	c	b	c	b	c	b	b
SECOND JOINT TEST RESULTS										
Failure Strength (psi)										
STATISTICAL DATA	Number of Data Points		Mean		Standard Deviation		Weibull Scale Parameter		Weibull Shape Parameter	
First Test Joint	10		3810 psi		300 psi		3950 psi		12.98	
Second Test Joint										
ADDITIONAL TEST INFORMATION	Failure strength was determined by dividing the failure load by the shear area of the joint of failure.									
	Each test specimen was soaked 60 min. @200°F prior to testing.									

TABLE XXIII

STATIC STRENGTH, T = 250°F, V = 120 LB/MIN

TEST TYPE										
First Joint	High Temperature Static Tensile Strength									
Second Joint										
FIRST JOINT	Temperature	Loading Rate or Frequency		Max. Fatigue Load Level			Fatigue Load Ratio (R)			
TESTING PARAMETERS	250°F	120 lb/min								
SECOND JOINT	Temperature	Loading Rate or Frequency								
TESTING PARAMETERS										
Specimen Number	233	247	260	278	281	291	300	317	319	349
FIRST JOINT TEST RESULTS										
Failure Strength (psi)	2520	2920	2880	2860	2430	2820	2670	2980	2770	2780
Cycles to Failure										
Joint of Failure	b	c	b	c	b	c	c	b	c	b
SECOND JOINT TEST RESULTS										
Failure Strength (psi)										
STATISTICAL DATA	Number of Data Points	Mean		Standard Deviation		Weibull Scale Parameter		Weibull Shape Parameter		
First Test Joint	10	2760 psi		180 psi		2840 psi		22.06		
Second Test Joint										
ADDITIONAL TEST INFORMATION	Failure strength was determined by dividing the failure load by the shear area of the joint of failure.									
	Each test specimen was soaked 60 min. @250°F prior to testing.									

TABLE XXIV

STATIC STRENGTH, T = 250°F, V = 1200 LB/MIN

TEST TYPE										
First Joint	High Temperature Static Tensile Strength									
Second Joint										
FIRST JOINT TESTING PARAMETERS	Temperature		Loading Rate or Frequency			Max. Fatigue Load Level			Fatigue Load Ratio (R)	
	250°F		1200 lb/min							
SECOND JOINT TESTING PARAMETERS	Temperature		Loading Rate or Frequency							
Specimen Number	288	299	301	307	316	320	323	330	342	350
FIRST JOINT TEST RESULTS										
Failure Strength (psi)	2250	2820	3280	3050	3170	3190	3040	3490	3260	3120
Cycles to Failure										
Joint of Failure	c	b	b	b	b	b	b	c	b	b
SECOND JOINT TEST RESULTS										
Failure Strength (psi)										
STATISTICAL DATA	Number of Data Points		Mean		Standard Deviation		Weibull Scale Parameter		Weibull Shape Parameter	
First Test Joint	10		3070 psi		340 psi		3190 psi		13.68	
Second Test Joint										
ADDITIONAL TEST INFORMATION	Failure strength was determined by dividing the failure load by the shear area of the joint of failure.									
	Each test specimen was soaked 60 min. @ 250°F prior to testing.									

TABLE XXV

STATIC STRENGTH, T = 250^{o}F, V = 12000 LB/MIN

TEST TYPE										
First Joint	High Temperature Static Tensile Strength									
Second Joint										
FIRST JOINT	Temperature		Loading Rate or Frequency			Max. Fatigue Load Level			Fatigue Load Ratio (R)	
TESTING PARAMETERS	250^{o}F		12000 lb/min							
SECOND JOINT	Temperature		Loading Rate or Frequency							
TESTING PARAMETERS										
Specimen Number	282	283	295	303	310	313	328	333	340	346
FIRST JOINT TEST RESULTS										
Failure Strength (psi)	3530	3560	2770	3360	3760	3150	3480	3210	3590	3290
Cycles to Failure										
Joint of Failure	c	c	c	b	b	c	b	b	b	c
SECOND JOINT TEST RESULTS										
Failure Strength (psi)										
STATISTICAL DATA	Number of Data Points		Mean		Standard Deviation		Weibull Scale Parameter		Weibull Shape Parameter	
First Test Joint	10		3370 psi		280 psi		3490 psi		16.01	
Second Test Joint										
ADDITIONAL TEST INFORMATION	Failure strength was determined by dividing the failure load by the shear area of the joint of failure.									
	Each test specimen was soaked 60 min. @250^{o}F prior to testing.									

TABLE XXVI

STATIC STRENGTH, T = 300°F, V = 120 LB/MIN

TEST TYPE										
First Joint	High Temperature Static Tensile Strength									
Second Joint										
FIRST JOINT	Temperature		Loading Rate or Frequency			Max. Fatigue Load Level			Fatigue Load Ratio ( )	
TESTING PARAMETERS	300°F		120 lb/min							
SECOND JOINT	Temperature		Loading Rate or Frequency							
TESTING PARAMETERS										
Specimen Number	58	61	69	70	75	80	83	85	90	94
FIRST JOINT TEST RESULTS										
Failure Strength (psi)	1590	1330	1670	1730	1620	1640	1140	1740	1770	1870
Cycles to Failure										
Joint of Failure	b	b	c	c	b	b	b	b	b	b
SECOND JOINT TEST RESULTS										
Failure Strength (psi)										
STATISTICAL DATA	Number of Data Points		Mean		Standard Deviation		Weibull Scale Parameter		Weibull Shape Parameter	
First Test Joint	10		1610 psi		220 psi		1690 psi		10.95	
Second Test Joint										
ADDITIONAL TEST INFORMATION	Failure strength was determined by dividing the failure load by the shear area of the joint of failure.									
	Each test specimen was soaked 60 min. @ 300°F prior to testing.									

TABLE XXVII

STATIC STRENGTH, T = 300°F, V = 1200 LB/MIN

TEST TYPE										
First Joint	High Temperature Static Tensile Strength									
Second Joint										
FIRST JOINT TESTING PARAMETERS	Temperature	Loading Rate or Frequency		Max. Fatigue Load Level			Fatigue Load Ratio (R)			
	300°F	1200 lb/min								
SECOND JOINT TESTING PARAMETERS	Temperature	Loading Rate or Frequency								
Specimen Number	2	4	6	10	12	14	16	17	20	22
FIRST JOINT TEST RESULTS										
Failure Strength (psi)	1690	1760	2080	2540	2190	2000	2070	2000	2010	2120
Cycles to Failure										
Joint of Failure	c	b	c	b	c	c	c	b	b	b
SECOND JOINT TEST RESULTS										
Failure Strength (psi)										
STATISTICAL DATA	Number of Data Points	Mean	Standard Deviation	Weibull Scale Parameter	Weibull Shape Parameter					
First Test Joint	10	2050 psi	230 psi	2150 psi	9.08					
Second Test Joint										
ADDITIONAL TEST INFORMATION	Failure strength was determined by dividing the failure load by the shear area of the joint of failure.									
	Each test specimen was soaked 60 min. @ 300°F prior to testing.									

TABLE XXVIII

STATIC STRENGTH, T = 300°F, V = 12000 LB/MIN

TEST TYPE										
First Joint	High Temperature Static Tensile Strength									
Second Joint										
FIRST JOINT	Temperature	Loading Rate or Frequency			Max. Fatigue Load Level			Fatigue Load Ratio (R)		
TESTING PARAMETERS	300°F	12000 lb/min								
SECOND JOINT	Temperature	Loading Rate or Frequency								
TESTING PARAMETERS										
Specimen Number	8	13	19	23	32	37	43	47	54	56
FIRST JOINT TEST RESULTS										
Failure Strength (psi)	2730	2910	2810	2850	2600	3040	2910	3070	2440	2510
Cycles to Failure										
Joint of Failure	b	b	b	b	b	b	b	b	b	b
SECOND JOINT TEST RESULTS										
Failure Strength (psi)										
STATISTICAL DATA	Number of Data Points	Mean		Standard Deviation		Weibull Scale Parameter		Weibull Shape Parameter		
First Test Joint	10	2790 psi		210 psi		2880 psi		16.51		
Second Test Joint										
ADDITIONAL TEST INFORMATION	Failure strength was determired by dividing the failure load by the shear area of the joint of failure.									
	Each test specimen was soaked 60 min. @ 300°F prior to testing.									

TABLE XXIX

FATIGUE, $T = 73^{o}F$, $F_{MAX} = 3100$ LB

TEST TYPE										
First Joint	Constant Amplitude Fatigue									
Second Joint	Residual Static Tensile Strength									
FIRST JOINT	Temperature	Loading Rate or Frequency		Max. Fatigue Load Level			Fatigue Load Ratio (R)			
TESTING PARAMETERS	73°F	5Hz		3100 lb			0.1			
SECOND JOINT	Temperature	Loading Rate or Frequency								
TESTING PARAMETERS	73°F	1200 lb/min								
Specimen Number	77	82	89	96	99	105	107	111	114	118
FIRST JOINT TEST RESULTS										
Failure Strength (psi)										
Cycles to Failure	8800	14,100	14,700	24,800	22,300	5000	9200	10,200	14,900	17,800
Joint of Failure	c	c	c	c	c	b	b	c	c	c
SECOND JOINT TEST RESULTS										
Failure Strength (psi)	5190	4500	5740	5360	-	5480	5410	-	3290	-

STATISTICAL DATA	Number of Data Points	Mean	Standard Deviation	Weibull Scale Parameter	Weibull Shape Parameter
First Test Joint	10	14,200 cycles	6,200 cycles	16,000 cycles	2.62
Second Test Joint	7	5000 psi	850 psi	5290 psi	9.71

ADDITIONAL TEST INFORMATION: Failure strength was determined by dividing failure load by the shear area of the joint of failure.

TABLE XXX

FATIGUE, T = 73°F, F_{MAX} = 2900 LB

TEST TYPE										
First Joint	Constant Amplitude Fatigue									
Second Joint	Residual Static Tensile Strength									
FIRST JOINT	Temperature		Loading Rate or Frequency			Max. Fatigue Load Level		Fatigue Load Ratio (R)		
TESTING PARAMETERS	73°F		5 Hz			2900 lb		0.1		
SECOND JOINT	Temperature		Loading Rate or Frequency							
TESTING PARAMETERS	73°F		1200 lb/min							
Specimen Number	64	68	74	79	84	91	98	103	113	116
FIRST JOINT TEST RESULTS										
Failure Strength (psi)										
Cycles to Failure	40,200	18,700	31,200	55,600	19,900	70,600	16,800	51,600	17,600	46,600
Joint of Failure	b	b	c	b	b	b	c	c	b	c
SECOND JOINT TEST RESULTS										
Failure Strength (psi)	5430	5460	-	4260	4500	4290	5370	4570	3240	4980
STATISTICAL DATA	Number of Data Points		Mean		Standard Deviation		Weibull Scale Parameter		Weibull Shape Parameter	
First Test Joint	10		36,900 cycles		19,000 cycles		41,900 cycles		2.22	
Second Test Joint	9		4680 psi		720 psi		4960 psi		8.67	
ADDITIONAL TEST INFORMATION	Failure strength was determined by dividing the failure load by the shear area of the joint of failure.									

TABLE XXXI

FATIGUE, T = 73°F, F_{MAX} = 2700 LB

TEST TYPE				
First Joint	Constant Amplitude Fatigue			
Second Joint	Residual Static Tensile Strength			
FIRST JOINT TESTING PARAMETERS	Temperature	Loading Rate or Frequency	Max. Fatigue Load Level	Fatigue Load Ratio (R)
	73°F	5 Hz	2700 lb	0.1
SECOND JOINT TESTING PARAMETERS	Temperature	Loading Rate or Frequency		
	73°F	1200 lb/min		

Specimen Number	51	52	53	55	59	60	62	66	67	71
FIRST JOINT TEST RESULTS										
Failure Strength (psi)										
Cycles to Failure	13,500	19,800	26,800	34,600	66,000	55,600	36,500	12,800	15,200	47,500
Joint of Failure	b	b	b	b	b	c	c	b	c	c
SECOND JOINT TEST RESULTS										
Failure Strength (psi)	4310	3880	5140	4270	4620	4870	5060	-	5500	-

STATISTICAL DATA	Number of Data Points	Mean	Standard Deviation	Weibull Scale Parameter	Weibull Shape Parameter
First Test Joint	10	32,800 cycles	18,700 cycles	37 300 cycles	1.99
Second Test Joint	8	4710 psi	540 psi	4930 psi	10.72

ADDITIONAL TEST INFORMATION	Failure strength was determined by dividing the failure load by the shear area of the joint of failure.

TABLE XXXII

FATIGUE, T = 73°F, F_{MAX} = 2500 LB

(Page 1 of 2)

TEST TYPE				
First Joint	Constant Amplitude Fatigue			
Second Joint	Residual Static Tensile Strength			
FIRST JOINT	Temperature	Loading Rate or Frequency	Max. Fatigue Load Level	Fatigue Load Ratio (R)
TESTING PARAMETERS	73°F	5 Hz	2500 lb	0.1
SECOND JOINT	Temperature	Loading Rate or Frequency		
TESTING PARAMETERS	73°F	1200 lb/min		

Specimen Number	50	57	63	65	72	73	76	81	86	92
FIRST JOINT TEST RESULTS										
Failure Strength (psi)										
Cycles to Failure	178,500	2.32×10^6	486,400	115,500	595,200	69,800	40,500	459,800	192,200	353,900
Joint of Failure	c	*	b	c	b	c	c	b	b	c
SECOND JOINT TEST RESULTS										
Failure Strength (psi)	4250	-	5120	4690	5480	5860	5280	4740	5150	4700

STATISTICAL DATA	Number of Data Points	Mean	Standard Deviation	Weibull Scale Parameter	Weibull Shape Parameter
First Test Joint	9*	276,900 cycles	201,900 cycles	305,000 cycles	1.43
Second Test Joint	9	5030 psi	490 psi	5240 psi	11.77

ADDITIONAL TEST INFORMATION

Failure strength was determined by dividing the failure load by the shear area of the joint of failure.

*Specimen 57 was removed from the load frame after 2.32×10^6 cycles without failure and was not included in the statistical data analysis above. Including this runout data point results in the following statistical data, N = 10, Scale Parameter = 480,700 cycles, Shape Parameter = 0.80.

TABLE XXXII

(Page 2 of 2)

TEST TYPE	
First Joint	Constant Amplitude Fatigue
Second Joint	

	Temperature	Loading Rate or Frequency	Max. Fatigue Load Level	Fatigue Load Ratio (R)
FIRST JOINT TESTING PARAMETERS	73°F	5 Hz	2350 lb	0.1
SECOND JOINT TESTING PARAMETERS	Temperature	Loading Rate or Frequency		

Specimen Number	88	186	198	203	218	223				
FIRST JOINT TEST RESULTS										
Failure Strength (psi)										
Cycles to Failure	137,200	38,700	316,000	812,500	28,400	126,100				
Joint of Failure	c	b	b	c	b	b				
SECOND JOINT TEST RESULTS										
Failure Strength (psi)										

STATISTICAL DATA	Number of Data Points	Mean	Standard Deviation	Weibull Scale Parameter	Weibull Shape Parameter
First Test Joint	6	243,200 cycles	297,400 cycles	233,000 cycles	0.92
Second Test Joint					

ADDITIONAL TEST INFORMATION	

TABLE XXXIII

FATIGUE, $T = 73^{\circ}F$, $F_{MAX} = 2150$ LB

(Page 1 of 2)

TEST TYPE										
First Joint	Constant Amplitude Fatigue									
Second Joint										
FIRST JOINT	Temperature		Loading Rate or Frequency			Max. Fatigue Load Level			Fatigue Load Ratio (R)	
TESTING PARAMETERS	73°F		10 Hz			2150 lb			0.1	
SECOND JOINT	Temperature		Loading Rate or Frequency							
TESTING PARAMETERS										
Specimen Number	193	195	201	207	210	217	219	226	230	252
FIRST JOINT TEST RESULTS										
Failure Strength (psi)										
Cycles to Failure	323,800	108,200	7.10×10^6	8.58×10^6	81,600	45,800	33,400	205,300	140,100	101,200
Joint of Failure	c	b	c	b	b	b	b	c	b	b
SECOND JOINT TEST RESULTS										
Failure Strength (psi)										
STATISTICAL DATA	Number of Data Points		Mean		Standard Deviation		Weibull Scale Parameter		Weibull Shape Parameter	
First Test Joint	8*		129,900 cycles		95,200 cycles		145,600 cycles		1.56	
Second Test Joint										
ADDITIONAL TEST INFORMATION										
	*Specimens 201, 207, and 255 were considered as being runout data points and were not included in the above statistical data analysis. Including these runout points results in the following statistical data, N = 11, Mean = 1.89×10^6 cycles, S.D. = 3.18×10^6 cycles, Scale Parameter = 880,200 cycles, and Shape Parameter = 0.50.									

TABLE XXXIII

(Page 2 of 2)

TEST TYPE				
First Joint	Constant Amplitude Fatigue			
Second Joint				
FIRST JOINT TESTING PARAMETERS	Temperature	Loading Rate or Frequency	Max. Fatigue Load Level	Fatigue Load Ratio (R)
	$73^{o}F$	10 Hz	2150 lb	0.1
SECOND JOINT TESTING PARAMETERS	Temperature	Loading Rate or Frequency		

Specimen Number	255									
FIRST JOINT TEST RESULTS										
Failure Strength (psi)										
Cycles to Failure	4.01×10^{6}									
Joint of Failure	b									
SECOND JOINT TEST RESULTS										
Failure Strength (psi)										

STATISTICAL DATA	Number of Data Points	Mean	Standard Deviation	Weibull Scale Parameter	Weibull Shape Parameter
First Test Joint					
Second Test Joint					

ADDITIONAL TEST INFORMATION	

TABLE XXXIV

FATIGUE, T = 73°F, F_{MAX} = 2000 LB

(Page 1 of 2)

TEST TYPE	
First Joint	Constant Amplitude Fatigue
Second Joint	Residual Static Tensile Strength

	Temperature	Loading Rate or Frequency	Max. Fatigue Load Level	Fatigue Load Ratio (R)
FIRST JOINT TESTING PARAMETERS	73°F	20 Hz	2000 lb	0.1

	Temperature	Loading Rate or Frequency
SECOND JOINT TESTING PARAMETERS	73°F	1200 lb/min

Specimen Number	228	240	243	253	259	271	275	286	292	306
FIRST JOINT TEST RESULTS										
Failure Strength (psi)										
Cycles to Failure	222,500	73,200	1.5×10^7	87,300	1.5×10^7	1.85×10^6	2.81×10^6	1.5×10^7	74,600	1.5×10^7
Joint of Failure	b	b	*	b	*	b	b	*	b	*
SECOND JOINT TEST RESULTS										
Failure Strength (psi)	4710	5260	-	4400	-	3320	4330	-	3050	-

STATISTICAL DATA	Number of Data Points	Mean	Standard Deviation	Weibull Scale Parameter	Weibull Shape Parameter
First Test Joint	9	1.13×10^6 cycles	1.54×10^6 cycles	861,100 cycles	0.69
Second Test Joint	9	4340 psi	720 psi	4620 psi	8.48

ADDITIONAL TEST INFORMATION: Failure strength was determined by dividing the failure load by the shear area of the joint of failure. *Specimens 243, 259, 286, 306, 325, and 341 were removed from the load frame after 1.5×10^7 cycles without failure and were not included in the above statistical data analysis. Including these runout data points results in the following statistical data, N=15, Scale Parameter = 13.9×10^6 cycles, and Shape Parameter = 0.36.

TABLE XXXIV

(Page 2 of 2)

TEST TYPE	
First Joint	Constant Amplitude Fatigue
Second Joint	Residual Static Tensile Strength

	Temperature	Loading Rate or Frequency	Max. Fatigue Load Level	Fatigue Load Ratio (R)
FIRST JOINT TESTING PARAMETERS	73°F	20 Hz	2000 lb	0.1

	Temperature	Loading Rate or Frequency		
SECOND JOINT TESTING PARAMETERS	73°F	1200 lb/min		

Specimen Number	309	325	335	341	352					
FIRST JOINT TEST RESULTS										
Failure Strength (psi)										
Cycles to Failure	195,200	1.5×10^{7}	4.33×10^{6}	1.5×10^{7}	494,700					
Joint of Failure	b	*	b	*	c					
SECOND JOINT TEST RESULTS										
Failure Strength (psi)	4480	-	4660	-	4870					

STATISTICAL DATA	Number of Data Points	Mean	Standard Deviation	Weibull Scale Parameter	Weibull Shape Parameter
First Test Joint					
Second Test Joint					

ADDITIONAL TEST INFORMATION

TABLE XXXV

FATIGUE, T = 200°F, F_{MAX} = 2000 LB

(Page 1 of 2)

TEST TYPE										
First Joint	High Temperature Constant Amplitude Fatigue									
Second Joint										
FIRST JOINT	Temperature		Loading Rate or Frequency			Max. Fatigue Load Level			Fatigue Load Ratio (R)	
TESTING PARAMETERS	200°F		20 Hz			2000 lb			0.1	
SECOND JOINT	Temperature		Loading Rate or Frequency							
TESTING PARAMETERS										
Specimen Number	265	268	276	285	293	294	297	308	314	324
FIRST JOINT TEST RESULTS										
Failure Strength (psi)										
Cycles to Failure	244,700	175,100	181,400	48,300	7,200	62,700	72,400	220,900	20,200	83,100
Joint of Failure	b	b	c	c	c	c	c	c	c	b
SECOND JOINT TEST RESULTS										
Failure Strength (psi)										
STATISTICAL DATA	Number of Data Points		Mean		Standard Deviation		Weibull Scale Parameter		Weibull Shape Parameter	
First Test Joint	15		101,200 cycles		75,700 cycles		110,100 cycles		1.34	
Second Test Joint										
ADDITIONAL TEST INFORMATION	Each test specimen was soaked 60 min. @ 200°F prior to testing.									

TABLE XXXV

(Page 2 of 2)

TEST TYPE										
First Joint	High Temperature Constant Amplitude Fatigue									
Second Joint										
FIRST JOINT	Temperature		Loading Rate or Frequency			Max. Fatigue Load Level			Fatigue Load Ratio (R)	
TESTING PARAMETERS	200°F		20 Hz			2000 lb			0.1	
SECOND JOINT	Temperature		Loading Rate or Frequency							
TESTING PARAMETERS										
Specimen Number	327	331	337	344	351					
FIRST JOINT TEST RESULTS										
Failure Strength (psi)										
Cycles to Failure	120,400	23,200	71,800	143,900	42,600					
Joint of Failure	c	c	c	c	b					
SECOND JOINT TEST RESULTS										
Failure Strength (psi)										
STATISTICAL DATA	Number of Data Points		Mean		Standard Deviation		Weibull Scale Parameter		Weibull Shape Parameter	
First Test Joint										
Second Test Joint										
ADDITIONAL TEST INFORMATION										

REFERENCES

1. Halpin, J.C., Jerina, K.L. and Johnson, T.A., in Analysis of the Test Methods for High Modulus Fibers and Composites, ASTM STP521.

2. Tsai, S.W., Halpin, J.C. and Pagano, N.J., Composite Materials Workshop, Technomic Publishing Co., Inc., Standford, Conn., 1968.

3. Halpin, J.C., "Structural Reliability Characterization of Advanced Composites," Proceedings of the Colloquium on Structural Reliability, Department of Mechanical Engineering, Carnegie-Mellon University, Pittsburgh, Pa., 1972.

4. Thoman, D.R., Bain, L.J. and Antle, C.E., Technometrics, Vol. II, No. 3, August, 1969, pp. 445-460.

5. Wolff, R.V. and Lemon, G.H., "Reliability Prediction for Adhesive Bonds," Technical Report AFML-TR-72-121, Air Force Materials Laboratory, Dayton, Ohio, 1972.

☆U.S.Government Printing Office: 1974 — 657-014/118